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Environmental Assessment: At-Sea and Land-Based Incineration of Organochlorine Wastes

TRW, Inc, Redondo Beach, Calif

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ENVIRONMENTAL ASSESSMENT: AT-SEA AND LAND-BASED INCINERATION OF ORGANOCHLORINE WASTES

Industrial Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

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by

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16. ABSTRACT The report provides a generalized description of at-sea and land-based incineration of organochlorine wastes and an assessment of their corresponding impacts. The data base for at-sea incineration was obtained during a series of burns, between April 1974 and March 1977. Data describing land-based incineration were obtained from a review of the literature, and a brief survey of companies involved in commercial use and manufacture of incinerators. The report includes: (1) typical organochlorine waste compositions, (2) descriptions of emissions produced during at-sea and land-based incineration, (3) a simulation of corresponding air quality changes, (4) a description of predicted paths of transport of emission constituents, (5) estimates of water quality changes associated with both types of incineration, (6) an assessment of the potential for malfunction which could produce adverse environmental effects, (7) a general discussion of the kinds of environmental impacts associated with the incineration processes, and (8) identification of areas where there are needs for upgrading existing systems and data gaps which limit the comprehensiveness of the analysis.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Waste Disposal	Pollution Control	13B
Incinerators	Organic Wastes	Environmental Assessment	13J 07B
Ships	Chlorine	At-Sea Incineration	08J
Sea Water	Industrial Processes	Land-Based Incineration	13H
Chlorine Organic Compounds		Organochlorine	07C

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PREFACE

The United States Environmental Protection Agency (EPA) is currently preparing an environmental impact statement (EIS) on the proposed use of an area in the North Atlantic as a "burn zone" for shipboard incineration activities. This report is being submitted to EPA as a support document to assist in the preparation of their EIS.

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LIST OF ABBREVIATIONS AND SYMBOLS

x	-- Ambient Concentration in Grams/Cubic Meters
C-5,6	-- Hexachlorocyclopentadiene
gm or g	-- Grams
h	-- Effective Stack Height
kcal	-- Kilocalorie
kg	-- Kilogram
km	-- Kilometer
kt	-- Knots
m	-- Meter
$\mu g/m^3$	-- Microgram/Cubic Meter (10^{-6} grams/cubic meter)
μm	-- Micrometer (micron, 10^{-6} meters)
mg	-- Milligram (10^{-3} grams)
mg/m^3	-- Milligram/Cubic Meter (10^{-3} grams/cubic meter)
m/s	-- Meters/Second
ng	-- Nanograms (10^{-9} grams)
nm	-- Nanometers (10^{-9} meters)
ppb	-- Parts Per Billion
ppm	-- Parts Per Million
Q	-- Pollutant Release, Emission or Discharge Rate
σ_y	-- Standard Deviation in Plume Width in Horizontal Direction
σ_z	-- Standard Deviation in Plume Width in Vertical Direction
tonnes	-- Metric Tonnes = 1000 kilograms

SECTION 1

BACKGROUND AND SUMMARY

BACKGROUND

Modern technological society produces large quantities of industrial waste. These wastes are comprised primarily of materials generated during manufacturing processes. According to a 1973 estimate, approximately nine million tonnes of toxic waste are produced every year within the United States [1]. More recent estimates have ranged from 30 to 40 million tonnes per year [2,3,4]. A sizable portion of the nation's toxic wastes are materials produced by the organic chemical manufacturing industry [3]. Table 1 presents preliminary estimates of the production of organic chemicals (as defined by Standard Industrial Classification (SIC) Codes 2861, 2865 and 2869), and corresponding wastes. Values are given for the years 1977, 1983 and 1989, with breakdowns for organochlorine production and resulting wastes. The derivation of these values is discussed in Appendix A.

TABLE 1. ESTIMATES OF NATIONAL ORGANIC CHEMICAL PRODUCTION AND CORRESPONDING WASTES

	Total Production (in thousand tonnes)		
	1977	1983	1989
Organic Chemicals	93,435	143,578	201,254
Organic Wastes	2,302	4,249	6,354
Organochlorines	13,340	20,500	28,730
Organochlorine Wastes	440	606	907

Source: See Appendix A

Prior to passage of the Marine Protection, Research, and Sanctuaries Act (MPRSA) of 1972 (Public Law 92-532), as amended (Public Law 93-254), some of the organochlorine wastes generated in the United States were dumped at designated ocean dumping sites under the auspices of the U.S. Army Corps of Engineers and the U.S. Coast Guard. MPRSA required that ocean dumping be

regulated under permit by the U.S. Environmental Protection Agency (EPA). Regulations promulgated as a result of MPRSA prohibited the direct dumping of several hazardous wastes including organochlorine wastes.

Other organochlorine waste disposal methods which have been used in the U.S. include recycling, chemical destruction, drum burial, pumping into sealed sites within geological formations, and land-based incineration [5,6]. U.S. chemical companies which needed to dispose of sizeable quantities of organochlorine wastes began investigation of another disposal alternative: at-sea incineration. This disposal method had been used extensively for European wastes and it attracted the attention of various U.S. companies with waste disposal problems. One claim was that at-sea incineration was environmentally acceptable for the disposal of organochlorine wastes. This claim was based on the following facts: 1) at-sea incineration activities take place 30 to 200 miles from shore (depending on regulations); 2) due to its high chloride concentration, seawater offers an attractive sink for inorganic chlorides in the combustion products; and 3) because seawater is highly buffered, it is capable of neutralizing HCl (one of the combustion products of organochlorine incineration) without undergoing any change in pH.

This report considers two alternative disposal procedures which can be effectively used for organochlorine wastes. The procedures are 1) land-based incineration, and 2) at-sea incineration utilizing shipboard incinerators. The primary purpose of this report is to provide a generalized description of the environmental impact associated with each system.

The data base for this analysis is comprised of field test results, personal contacts with manufacturers and operators of incinerator facilities, modeling and simulation, and information from selected resources in the literature. The overall approach consisted of the following elements: 1) identification of combustion products generated by organochlorine incineration at land-based and at-sea facilities, 2) general characterization of the transport and fate of these materials within air, water and land environments; and 3) identification and prediction of general environmental impacts that may result from the effects of these combustion products.

EPA has proposed the designation of an area in the North Alantic to be used for at-sea incineration activities. The coordinates of the proposed burn zone are given below:

Latitude	Longitude
39° 40'N	72° 0'W
39° 0'N	72° 30'W

This locates the burn area approximately 145 km east of Capy May, New Jersey. Figure 1 shows the position of the proposed burn zone in relation to the northeastern coast of the United States. At-sea incineration analyses in this report will be focused on this location.

Discussions concerning land-based incineration will be based primarily on data obtained during incinerator test burns at a facility considered to be representative of the commercial waste disposal industry.

Some limitations apply to the analysis. First, the emphasis of the report will be liquid injection incinerators. However, the analysis presented in this report is based primarily on environmental effects of combustion products. Organochlorine materials having identical elemental compositions and undergoing similar destruction efficiencies will yield similar combustion products regardless of 1) physical state (i.e. liquid or solid) of the initial material or 2) type of incinerator used. One would not expect combustion production products to be exactly the same, notable differences being these listed below:

- Burning of solids may leave an ash residue and the resulting combustion gases may have a higher particulate loading.
- Atomization of liquid wastes during injection into the incinerator produces droplets which are likely to be much smaller than the parcels which undergo combustion during the incineration of solid wastes. Because larger particles take longer to burn, solid wastes may require longer retention times to achieve the same destruction efficiency.

Secondly, the discussion of environmental impacts will not deal with the problems encountered during the transportation of waste from the waste generator to the disposal facility.

Time limitations have prevented a comprehensive literature survey. In many cases, the incinerator operators contacted were reluctant to

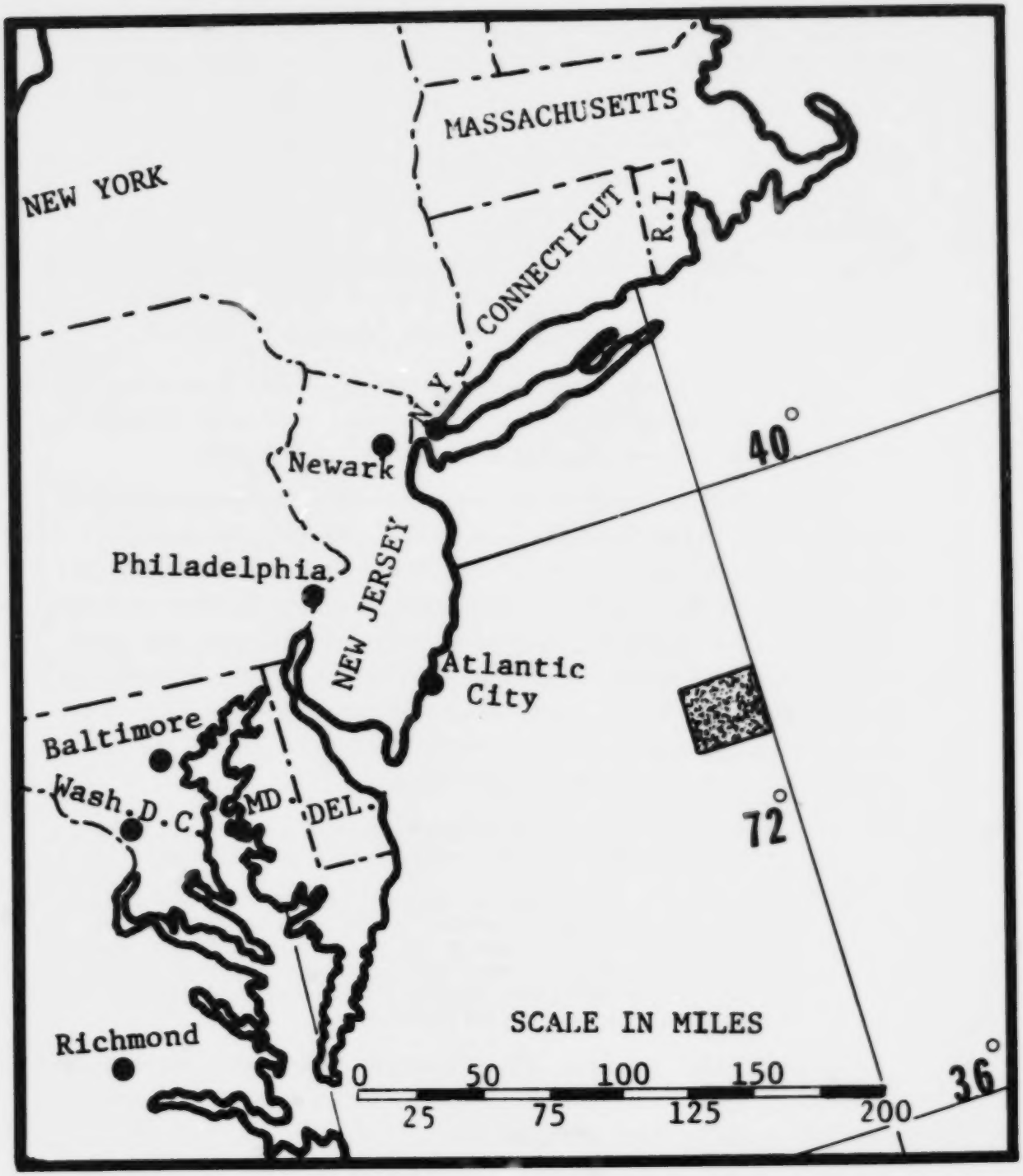


Figure 1. Location of Proposed Burn Zone (Shaded Area).

provide detailed information describing their process operation. Therefore, there will be topics not covered, and the description of the land-based facility will rely to some extent on field tests performed previously, personal experience and engineering judgment.

SUMMARY

This report provides a description of at-sea and land-based incineration systems and an assessment of corresponding environmental impacts. Major finding of the analysis are summarized below. Statements listed are generalizations that apply to the generic categories of land-based and at-sea incinerator systems.

- A major difference between at-sea and land-based incineration is the pathway by which combustion products exit the facility. For land-based facilities, the combustion products are transferred primarily to the scrubber water and this represents a major impact route. With at-sea systems, combustion products go directly to the atmosphere, from which they are partitioned between air and water environments.

- Major uncertainties and data gaps for the at-sea incineration system relate to the:

  - Size distribution and compostion of particulates produced.
  - Need for data to better describe the ultimate fate of plume and plume constituents during the typical "coning aloft" pattern of plume behavior (i.e., where the plume does not seem to touch the down).
  - Extent to which HCl in plume could add to acid rain problems.

- Major uncertainties and data gaps for the land-based incineration system relate to the extent to which:

  - Solids removed from the incinerator or entrained in scrubber water contain heavy metals and unburned wastes.
  - Heavy metals and unburned wastes are dissolved in scrubber water.
  - Effects on land and groundwater quality (via leachate from landfills) are site specific and depend on the soil characteristics.
  - Details on plant operations are available.

- Incineration is attractive because available technology can attain greater than 99.9% destruction efficiency.

- The compostion of wastes being destroyed in the incinerator must be determined. Waste compostion determines the nature of the emissions and the resulting environmental impact.

- More fail-safe and contingency plans in case of malfunction upset, or accident have been developed for at-sea incineration than for its land-based counterpart.

- In case of catastrophic or periodic malfunction accidents at either facility, the potential for acute adverse effects on the environment is greater at the land-based facility due to its close proximity to population centers, and areas of environmental concern.

- Land-based facilities utilizing alkaline scrubber water may contribute additional total dissolved solids (TDS) to water resources. Depending on the organochlorine waste incinerated, the scrubber wastewater could have TDS values higher than seawater. For inland areas, discharge of wastewater with TDS values approaching or higher than seawater will have a more significant impact because there is not an ocean nearby to serve as an appropriate sink.

- Land-based facilities with HCl recovery scrubbers may provide an opportunity for resource recovery, depending on the purity of HCl produced and market demand.

- At-sea systems can effectively dispose of organochlorine wastes at a much faster rate than land-based facilities. If land-based facilities utilized scrubber water in proportion to that which would be needed if they had comparable feed rates, the scrubber wastewater problems would increase significantly.

SECTION 2

ORGANOCHLORINE WASTES, EMISSIONS AND TRANSPORT PATHS

GENERAL DESCRIPTION OF ORGANOCHLORINE WASTES AND EMISSIONS

Organochlorines can be generally defined as that family of synthetic organic compounds which contain chlorine, carbon, and hydrogen. For the purposes of this report, oxygen could also be a constituent of an organochlorine, because the presence of this element would have no effect on the nature of the combustion products produced during incineration. On the other hand, the presence of nitrogen, sulfur, or phosphorus in combination with the above elements would generate different types of emissions (probably NO_2, SO_2, and P_2O_5, depending on combustion conditions). Therefore, organic compounds containing nitrogen, sulfur and phosphorus will not be considered in great detail, and only brief mention will be made of impacts associated with the incineration of these compounds.

In addition to the major elemental constituents of organochlorine wastes (i.e., Cl, C, H and possibly O) other elements are expected to be present in trace quantities. These may include metals (such as cadmium, lead, mercury, and chromium) and various organic contaminants. However, there are stringent controls for both at-sea and land-based incineration of organochlorine wastes containing metals. The Intergovernmental Maritime Consultative Organization (IMCO) has guidelines for at-sea incineration, and the U.S. Government has regulations and permit requirements which also apply to this type of activity [7,8]. For land-based facilities, regulations promulgated as a part of the Resource Conservation and Recovery Act (RCRA) will establish: (1) limits on the kinds of materials amenable to land-based incineration, and (2) performance standards describing appropriate disposal procedures. Controls for both at-sea and land-based incineration activities will have the ultimate effect of imposing limits on the kinds and quantities of trace constituents contained in organochlorine wastes to be incinerated.

Organochlorine wastes are generally produced during chemical manufacturing and other industrial processes. Specific categories of compounds include a large number of pecticides (e.g., DDT, 2,4,5-T, aldrin,

dieldrin, kepone, etc.) which may have been off-specification or in surplus and a series of low molecular weight chlorinated aliphatic hydrocarbons produced as non-salable wastes during organic synthesis reactions (e.g., vinyl chloride monomer wastes). The percent chlorine content of organochlorines is variable. Some wastes can contain as little as 10% or less chlorine, while hexachlorocyclopentadiene (C-5,6) production wastes may contain as much as 77% chlorine [9]. The average chlorine content of the organochlorine wastes generated in 1975 was 60.6% [6].

Throughout this report, emphasis will be placed on an organochlorine waste material generated during the production of vinyl chloride monomer and other chemicals at Shell Oil Company's Deer Park, Texas plant. This waste will often be referred to as "Shell waste." Emissions data are available for at-sea incineration activities involving Shell wastes. However, no emissions data are available for the incineration of this waste at land-based facilities. Therefore, the analysis concerning land-based incineration will be based on data obtained during the incineration of other liquid organochlorine wastes at these facilities. Emissions data were selected to be representative of the emissions expected to be produced during the incineration of Shell wastes.

Combustion of a simple organochlorine is described by:

$$CHClCCl_2 + 2O_2 \longrightarrow 2\ CO_2 + HCl + Cl_2$$

Water is also a combustion product. The above is a theoretical chemical reaction. In practice, controlling temperature and other combustion parameters results in limiting chlorine production to negligible amounts.

Thus, under optimal combustion conditions, the major products resulting from organochlorine combustion are CO_2, HCl and H_2O. Trace inorganics present in the initial wastes will also be found in the combustion products. The amount of CO and unburned waste will depend on the completeness of combustion.

Combustion efficiency (CE) and destruction efficiency (DE) are two parameters often used to describe an incinerator's effectiveness in disposing of organic wastes. The CE value for a certain burn is based on

measurements of CO and CO_2 concentrations of the hot gases leaving the combustion chamber. The expression which is usually used to make this determination is

$$CE\ (\%) = \frac{C_{CO_2} - C_{CO}}{C_{CO_2}} \times 100$$

where

C_{CO_2} = measured concentration of carbon dioxide

C_{CO} = measured concentration of carbon monoxide

Carbon monoxide and carbon dioxide concentrations must be expressed in the same units.

Destruction efficiency is basically a measure of the difference between the amount of wastes being fed to the incinerator and the amount of waste contained in the exiting gas stream. A variety of sampling, analysis, and calculation procedures can be used to determine the destruction efficiency of a particular burn. Table 2 lists four alternative methods of determining destruction efficiency. These methods are among those used for recent at-sea incineration tests [10]. If combustion is very complete, waste material will often be undetectable within final stack emissions. In such a situation, the detection limit of the analysis technique can be used to provide an upper bound on the amount of material which could be in the gas stream.

PROJECTED PATHS OF EMISSION CONSTITUENT TRANSPORT

In general, the efficient combustion of organochlorine generates the following categories of combustion products:

- Hydrogen chloride (proportional to chlorine in waste).
- Unburned waste components in trace amounts.
- Particulates which could contain salts of trace metals, and/or adsorbed unburned wastes.
- Small amounts of clinker or ash-like materials which do not leave with the stack gases, but form as deposits on the incinerator burner or interior walls.

TABLE 2. DEFINITION OF DESTRUCTION EFFICIENCY TERMS

Destruction Efficiency Term	Method of Efficiency Calculation	Description of Method
DE_{THC}	$\frac{\text{THC fed - THC from on-line monitor}}{\text{THC fed}} \times 100$	Total organic destruction efficiency based on total hydrocarbons (THC) measured by a continuous on-line monitor on board the Vulcanus.
DE_{GGHC}	$\frac{\text{THC fed - THC in grab gas sample}}{\text{THC fed}} \times 100$	Total organic destruction efficiency based on total hydrocarbons measured grab gas samples.
$DE_{SC_3Cl_3}$	$\frac{C_3Cl_3 \text{ fed} - C_3Cl_3 \text{ in SASS}^a \text{ samples}}{C_3Cl_3 \text{ fed}} \times 100$	Waste destruction efficiency based on trichloropropane (a major waste constituent) found in SASS[a] train samples. Trichloropropane was identified and quantified by GC/MS.[b]
$DE_{GGC_3Cl_3}$	$\frac{C_3Cl_3 \text{ fed} - C_3Cl_3 \text{ in grab gas samples}}{C_3Cl_3 \text{ fed}} \times 100$	Waste destruction efficiency based on trichloropropane (a major waste constituent) found in grab gas samples by GC after Tenax concentration.

[a] EPA's Source Assessment Sampling System

[b] Gas chromatography/mass spectrometry (an analysis technique)

Source: Reference 10

- Other innocuous gases (CO_2 and H_2O).
- Carbon monoxide.

The pathway taken by a constituent as it exits the incinerator varies with the type of incinerator, nature of the constituent, and operating practices.

Land-Based Incineration

For the most part, the analysis presented in this section (and generally throughout the report) will be based primarily on information obtained during monitored incineration runs at a land-based facility deemed to be representative of modern commercial disposal operations [11]. Emissions data are not available for the incineration of Shell wastes at this facility. However, selected data obtained during the incineration of other materials at this facility, and other materials at other facilities were used to provide an indication of the behavior of emission constituents.

Contaminants will be transported from the land-based incineration system as constituents of the flue gas, the scrubber water effluent, and solid residue.

Table 3 gives the composition of organochlorine wastes as reported in various studies of land-based incineration facilities. It can be expected that prior to entry into the scrubbing system over 99.9% of the chlorine in the organochlorine waste will be converted to hydrogen chloride. Depending on the destruction efficiency of the incinerator, not more than 0.05% of the original mass of chlorine will be present in the form of unburned organochlorine wastes, and as reported (no Cl_2 detected, 0.33 ppm detection limit [9]) it is expected that negligible amounts of the original mass of chlorine will appear as Cl_2 in stack gases.

Even though the destruction efficiency of the incinerator is not 100%, test results from several land-based systems indicated that no organic wastes were found in the scrubbing water, and none was detected in the

TABLE 3. SUMMARY ANALYTICAL DATA FOR ORGANOCHLORINE WASTES BURNED AT SELECTED LAND-BASED FACILITIES

Elemental Analysis

Element	Composition, %
Carbon	20.76 - 54.80
Hydrogen	0.67 - 2.80
Nitrogen	0.008 - 8.92[a]
Sulfur	0.019 - 0.22
Chlorine	23.28 - 76.47

Trace Elements

Element	Concentration, ppm
Chromium	12 - 25
Copper	1.9 - 13
Manganese	0.33 - 28
Lead	7 - 800 (ppb)
Arsenic	1 - 600 (ppb)
Mercury	10 (ppb)
Barium	36 - 5000 (ppb)
Cobalt	42 (ppb)
Selenium	3 - 600 (ppb)
Vanadium	4 - 600 (ppb)
Aluminum	10
Zinc	16
Fluorine	800 (ppb)
Iron	28
Silicon	28
Calcium	28
Sodium	28

Source: This table is a summary of data presented in References 9, 10, 11, 12 & 13.

[a]This relatively high nitrogen composition reflects inclusion of nitrochlorobenzene wastes burned at the facility considered to be representative of commercial incineration. If this compound were not included in the table, nitrogen levels would range up to a maximum of 0.37%.

stack gases. This indicates that the overall destruction efficiency of the system is better than 99.999% (via calculations based on detection limits of analysis method).

Various trace metals in the organochlorine wastes will be transported from the system in all of the previously mentioned modes. The greatest concentration of these contaminants will appear in the solids that result from combustion. Generally, solid residues produced during incineration of materials such as the Shell wastes will leave the incinerator as particulates in hot combustion gases. Most of these particulates will be removed during the scrubbing process and become either suspended or dissolved solids within the scrubber wastewater. Suspended solids contained in scrubber wastewater will end up as a sludge which will accumulate in holding tanks or other types of impoundments such as settling or evaporation ponds. Other precipitates may be formed within scrubber wastewater due to intentional or unintentional pH changes and other chemical reactions.

Particulate material which dissolves in the scrubber water will contribute to the total dissolved solids (TDS) content of this wastewater stream. Additional TDS contributions are due to 1) absorption of HCl, 2) use of alkaline materials in scrubber water to facilitate HCl removal via acid-base neutralization reactions, and 3) salts which result from these reactions.

In some cases, a solid residue will form on tips of the burners or walls of the incinerator. These materials (called clinkers) are not generally produced in large amounts, but analyses obtained at one land-based installation show that they contain trace metals and high percentages of carbon (88-99%) [9].

Some of the trace metals may be emitted from the stack either as constituents of particulate emissions or in some other form. These results show trace metals such as lead to be present in stack gases in concentrations of 3 to 5 $\mu g/m^3$ [12].

The overall quality of the scrubber water can range from 1800 to 50,000 mg/liter of total dissolved solids. Generally speaking, 1300 to 11,000 mg/liter are composed of chlorides. The remainder will be made up of sodium, various inorganics and trace metals. Tests at one facility

indicated that the concentration of heavy metal is less than 10 ppm. This is the maximum allowable concentration for wastewater entering the sewers which serve this facility. Table 4 gives the breakdown of trace metals found in the scrubber wastewater [9].

The hygroscopic contaminants, such as NaCl and any heavy metal salts, upon release to the atmosphere could act as cloud condensation nuclei and be washed from the atmosphere by rain or be removed by normal fallout. The other chlorides present will undergo the types of chemical reaction previously outlined.

The solid residue, clinker, and residue from scrubbing water settling tanks or evaporation ponds could contain several potentially hazardous materials, for example, the concentration of lead can range from 10 to 50 mg per kg of residue. In order to insure the least adverse effects from such elements, which have an accumulative effect on animal life, they should be properly disposed of in accordance with federal guidelines mandated by the Resource Conservation and Recovery Act of 1976 (RCRA).

At-Sea Incineration

The analysis presented here will be based primarily on data obtained during the March 1977 cruise of the M/T Vulcanus.

TABLE 4. TRACE METAL CONCENTRATIONS IN SCRUBBING SOLUTION FROM A LAND-BASED INCINERATION FACILITY

Element	Concentration, ppm
Copper	0.07 - 0.23
Chromium	0.01 - 0.38
Lead	0.02 - 0.54
Zinc	0.12 - 0.74
Manganese	0.06 - 0.59
Cobalt	0.05 - 0.12
Antimony	0.18 - 0.24

Source: Reference [9].

Table 5 gives the elemental composition of organochlorine wastes as reported in various studies conducted on wastes incinerated at sea. Because there is no scrubbing system, combustion products will be transported from the system as constituents of stack gas or of any solid residue formed during combustion. Observers of the at-sea incineration process have indicated that the small amount of clinker formed is knocked loose and dropped back into the combustion zone [14]. Therefore, it will be assumed that 100% of the matter entering the combustion system will exit via the stack gases and be released to the atmosphere. Stack test results indicate that less than 0.005% of the organic wastes are present in the stack gas. Destruction efficiency is, therefore, over 99.995%.

More than 99.9% of the chlorine in the waste will be converted to hydrogen chloride and emitted to the atmosphere. Although the fate of the gaseous hydrogen chloride once it exits the stack is not totally understood, the surface of the ocean has a pH of 8.3 and is an excellent sink for gaseous hydrogen chloride [15].

Unburned organochlorine wastes will be present in stack gas only in amounts which are well below detection limits. Photochemical reactions may cause this waste to be broken down into its hydrocarbon constituents and chlorine in the atmosphere. These hydrocarbons and chlorine will be removed from the atmosphere by rain and gas-to-liquid interactions (either physical or chemical) at the ocean's surface, or, if they reach land, they may be removed by interaction with soil or be taken up by vegetation in gas exchange [17,18]. However it should be stressed that at all points in this process, the hydrocarbons and chlorine from unburned organochlorines will be in concentrations well below detection limits.

During the March 1977 Vulcanus burn of Shell wastes, solid residues accumulated on burner heads. Frequent routine cleaning of the burners was necessary to remove these deposits. Samples of the residues were analyzed, and results showed the presence of all major Shell waste constituents (many at the 0.1 g/kg level). Other materials were found including organics (some chlorinated) considered to be polymeric tars [10]. It is

TABLE 5. ELEMENTAL ANALYSIS OF ORGANOCHLORINE WASTES (SHELL WASTE) BURNED AT SEA DURING U.S. EPA MONITORED TESTS

Elemental Analysis

Element	Composition Range, %
Carbon	29.0 - 30.01
Hydrogen	4.0 - 4.17
Nitrogen	0 - 0.012
Sulfur	0 - 0.009
Chlorine	62.6 - 63.5

Trace Elements

Element	Concentration, ppm
Cu	0.51 - 1.1
Cr	0.1 - 0.33
Ni	0.25 - 0.30
Zn	0.14 - 0.30
Pb	0.05 - 0.06
Cd	0.001 - 0.0014
As	<0.01
Hg	0.001 - 0.002
Si	<500
P	50 - 500
Ti	50 - 500
Ca	<25
Br	Trace

Source: This table is a summary of data presented in References 10, 16 and 17.

not known exactly how the total mass of the burner head residues compares with the mass of wastes burned, but it is probable that burner residues represent a small percentage.

Trace metals present in the organochlorine wastes will be released into the atmosphere in quantities equal to the amount present in the waste feed stock. As mentioned in a previous section, regulatory controls will allow at-sea incineration of only those wastes with acceptable trace metal levels. Various trace elements, particularly heavy metals found in the organochlorine waste, will most likely exit the stack in the form of salts as part of the particulate loading. It has been reported that only random traces of these elements were found in samples taken of ocean water, and only random slight increases in the concentration of metals such as copper were noted [17]. Therefore, it can be assumed that trace metals will be well dispersed throughout the plume and will be removed from the atmosphere by washing (e.g., by rain) or by fallout.

SECTION 3

LAND-BASED ALTERNATIVE

GENERAL DESCRIPTION

This section describes the land-based incineration industry. The description is based on data obtained from incinerator manufacturers [19], companies which incinerate various wastes [20,21,22,23,24], and the results of field testing performed by TRW as a part of their program "Destroying Chemical Wastes in Commercial Scale Incinerators," EPA Contract Number 68-01-2966 [9,11,12,13]. Some of the information that will be presented does not apply specifically to the incineration of organochlorine wastes, but this information does provide a representative picture of the general state of the art.

Incineration Process

Land-based incineration of heavily chlorinated materials requires two basic components, the combustion chamber and the scrubber. Figure 2 shows these two components in relation to other supporting elements of land-based incineration facilities. There are many variations of the process in current use. If the heating value of the organochlorine waste is below 3000 kcal/kg, it is mixed with auxiliary fuel either prior to or during injection with combustion air through a burner into the combustion chamber. At this point the mixture is ignited and the organic content of the waste is destroyed. Typically, liquid incinerators use throat mixing burners where the liquid waste is atomized to increase the surface area available for thermal destruction. One example of a throat mixing burner is the vortex type burner shown in Figure 3. The vortex burner operates by feeding combustion air into the chamber tangentially to the flow, thus producing a vortex. This process tends to increase turbulence and prolongs residence times, thereby improving completeness of combustion.

Combustion products of heavily chlorinated organochlorine wastes are usually passed through a scrubber after leaving the combustion chamber. Such scrubbers are designed to remove primarily particulates and HCl, but other combustion products may also be abstracted (e.q., NO_x, Cl_2, soluble organics, etc). The most common type of scrubber system consists of a venturi scrubber followed by a packed tower or a separator tank with a

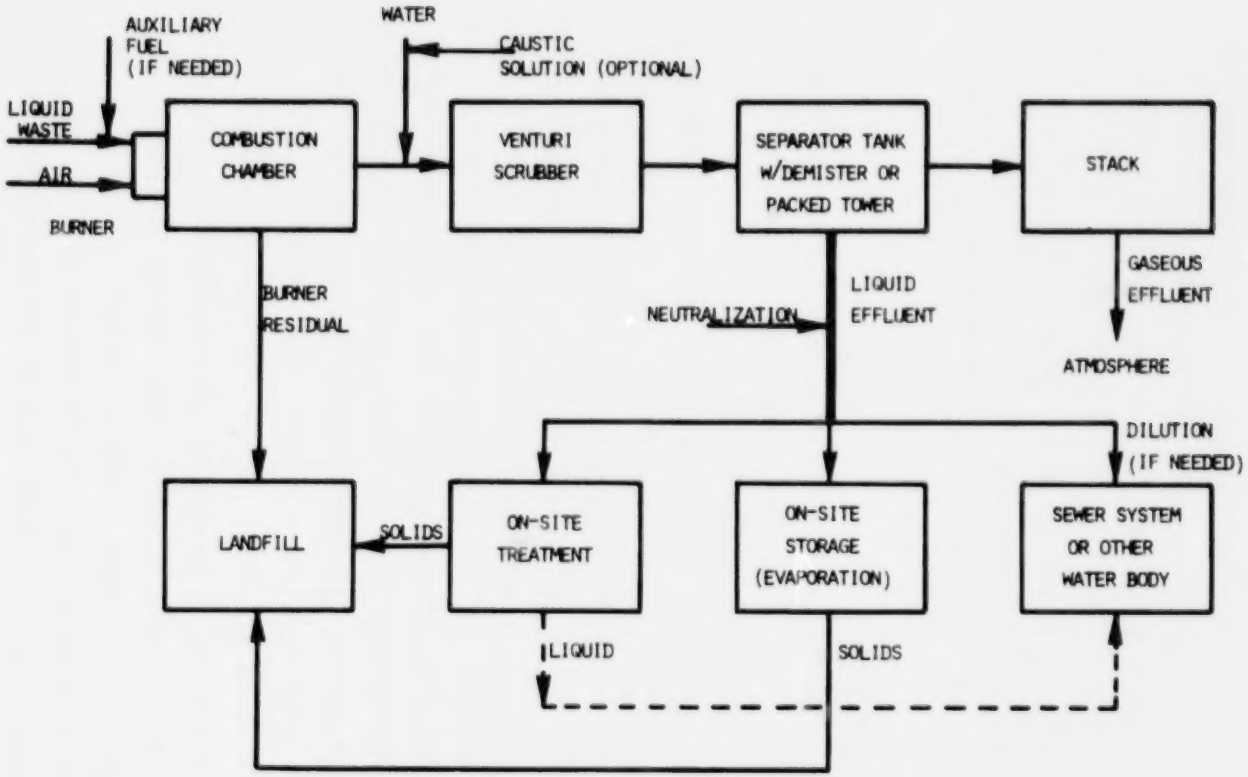


Figure 2. Land-based incineration process.

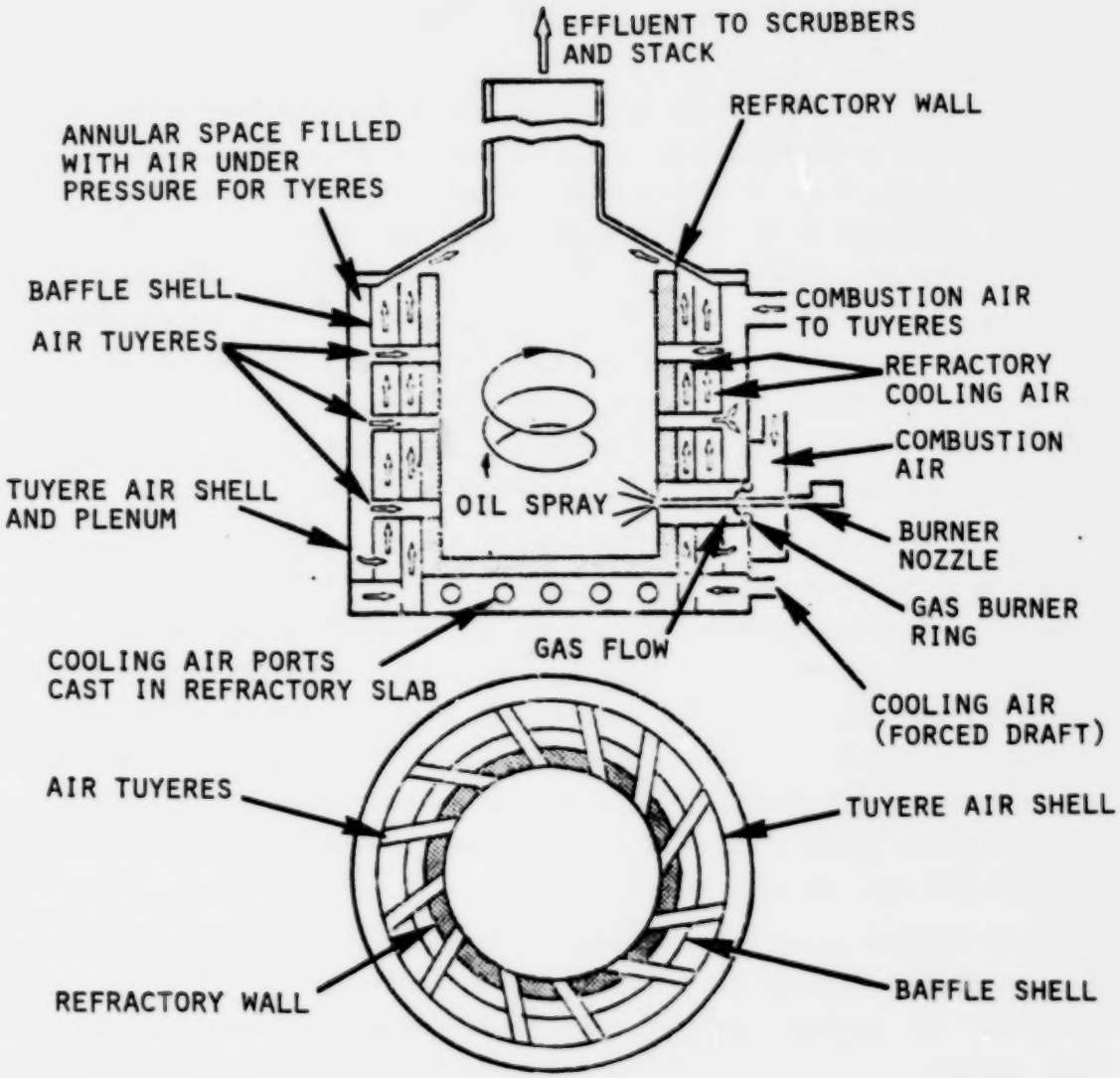


Figure 3. Vortex liquid waste incinerators.

Source: Reference [35].

demister. Figure 4 shows the system at one disposal facility [9]. In the venturi scrubber, the combustion gases are passed through a venturi tube which constricts the flow, and thereby causes high gas velocities. At the point of constriction, low pressure water and in some cases caustic are added to enhance removal of the HCl formed during combustion. There is very short contact time in the throat of the venturi. However, the extreme turbulence in the venturi promotes intimate contact, predominantly by impaction.

The venturi scrubbing process involves either a single pass of the scrubbing fluid or recirculation of the scrubbing fluid. If recirculation is used, scrubber fluid is recirculated through the venturi scrubber until the total dissolved solids (TDS) content reaches approximately 3% [22]. When this occurs, a portion of the scrubbing fluid is removed (blowdown) and new scrubbing fluid is added to make up for the fluid lost as blowdown. The blowdown from the single pass or recirculation scrubbing systems is neutralized (as needed) before delivery to on-site wastewater treatment processes, on-site storage facilities (e.g., evaporation ponds), or dispensing to the municipal sewer or a receiving water body.

Alternative types of scrubber systems have been designed to recover HCl produced during organochlorine incineration. Such systems can produce commercial grade hydrochloric acid streams with concentrations ranging between 20% and 60% HCl [22]. These systems utilize aqueous solutions to absorb HCl from the combustion chamber effluent gas stream, and the resulting solution is concentrated via water extraction procedures. Residual HCl that may be left in the remaining combustion gas stream can be removed by passing this stream through an alkaline neutralization tower, or by using conventional gas scrubbing procedures.

With regards to scrubber systems, the emphasis of this report will be directed towards scrubbers which remove HCl primarily by neutralization reactions. HCl recovery systems were mentioned to highlight the fact that they represent a viable alternative to conventional scrubbing techniques. Such systems may assume greater importance and use in response to the implementation of RCRA.

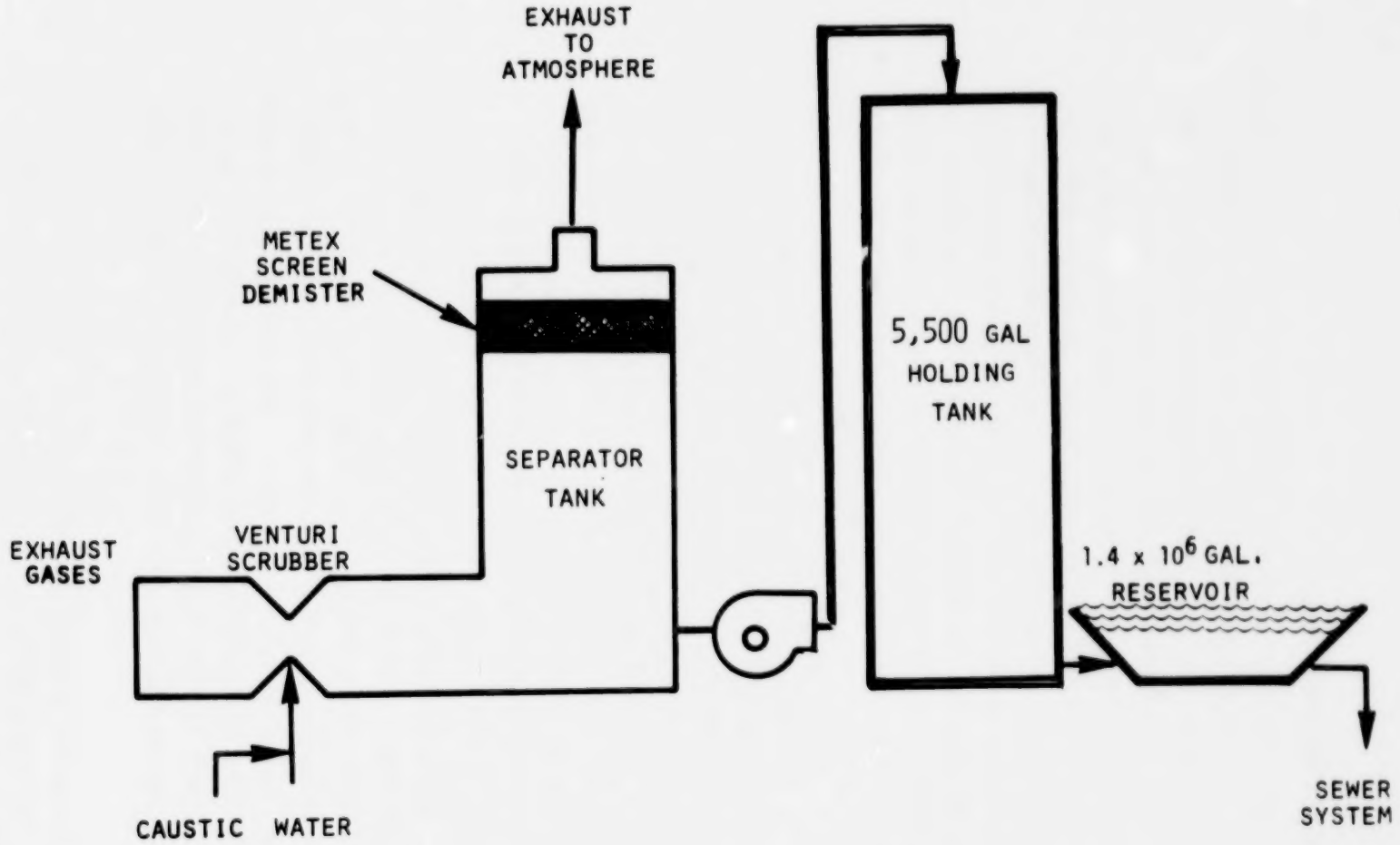


Figure 4. Flow sheet of scrubber water at a land-based incinerator

Operation Parameters for Incinerators

As a result of a review of available literature, contact with incinerator manufacturers, and field sampling experience, a variety of parameters have been identified which are often used in describing incinerators and their operation. These parameters include the incinerator's waste feed rate, design heat release rate, residence time of materials in the combustion zone, temperatures achieved, destruction and/or combustion efficiency achieved, and frequency of incinerator use. It is reasonable to expect that the values of these parameters will vary with different incinerators located at different disposal facilities. Therefore, the information presented below regarding these parameters represents ranges of values which may be observed at various industrial installations and commercial disposal facilities.

An incinerator's capacity for disposing of wastes is generally described in terms of its waste feed rate and design heat release rate. Units for expressing waste feed rate depend on the type of waste being incinerated. For incinerators which accept solid wastes, feed rates are listed in terms of pounds per hour or kilograms per hour. If the wastes are in liquid form, units of gallons per hour or liters per hour are used. Volumetric rates can be converted to mass feed rates if the density of the waste is know. For wastes with high heat contents, the waste feed rate may also be limited by the design heat release rate.

Because the emphasis of this report is directed at incinerators capable of burning liquid organochlorine waste, this was the main type of incinerator considered in our survey. Feed rates for incinerators in the facilities surveyed ranged from 80 liters per hour (20 gallons per hour) to 2840 liters per hour (750 gallons per hour). The incinerators involved in a recent TRW Program ("Destroying Chemical Wastes in Commercial Scale Incinerators") had heat release capabilities which ranged from 15 million kcal/hour (59 million Btu/hour) to 28 million kcal/hour (110 million Btu/hour).

For the incinerators surveyed, residence times varied from 0.111 to 12 seconds [12] and temperatures achieved ranged from 870°C to 1378°C (1500°F to 2500°F).

Frequency of incinerator use depends on the amount of wastes available for incineration, the rate at which the waste is incinerated, and periodic shutdown of the plant as required by normal maintenance. Some commercial waste disposal facilities receive enough waste to keep their incinerators operating 24 hours per day, 7 days per week [11]. At other facilities, incinerators may be operated only as long as there is waste available to burn.

Some wastes have heat contents which are too low to support combustion at temperatures required for adequate destruction. In these situations, such wastes are blended with other wastes with higher heat contents, or supplemented with fuel oil. These procedures are performed prior to injection or concurrent to the feeding of the waste into the incinerator.

General Description of Emissions

Available data were used to develop a general description of the nature and quantities of emissions that have been measured at facilities incinerating organochlorine wastes. Three types of emissions considered are stack gases, scrubber wastewater and solid residues.

Stack Gases

Reports studied [9, 11, 12, 13] show that the waste destruction efficiencies reached in liquid incineration processes are better than 99.99%. In only one case was the demonstration efficiency less than 99.999%. Waste constituents were not detected in combustion zone gases or in stack gases being vented to the atmosphere. The particulates found in the stack gases were in concentrations generally less than 100 milligrams per cubic meter (mg/m^3) [12]. At a facility considered to be typical of those capable of accepting organochlorine wastes, the measured particulate loading varied between 14 and 16 mg/m^3 [11].

Scrubber Wastewater

As mentioned previously, scrubbing processes for organochlorine incineration systems are designed to remove combustion products which may have adverse impacts if emitted directly to the atmosphere. Constituents in this category are HCl, particulates, and any trace amounts of unburned waste that may be present.

If water is the scrubbing fluid, the wastewater effluent will contain suspended particulates, dissolved HCl (i.e., hydrochloric acid), and other soluble constituents which may be present (e.g., trace quantities of organics and waste constituents that may be soluble). If alkaline scrubbing solutions are used, the HCl will undergo neutralization reactions to produce additional water and salts (either NaCl or $CaCl_2$ depending on whether NaOH or $Ca(OH)_2$ was used in the scrubbing solution). Because alkaline materials are often used in excess, residual amounts of these substances will be present. The wastewater will also contain suspended particulates and any soluble combustion products. Available analysis data of scrubber wastewater from incinerators burning organochlorine wastes showed no measurable amount of these wastes [9,11]. Furthermore, the concentration of trace metals was in the ppm range prior to on-site treatment. In general, total dissolved solids (TDS) concentrations usually ranged from 500 to 50,000 mg/liter.

Solid Residues of Combustion

The generation of solid residues from the burning of Shell wastes is not expected to be a significant problem. Observations made during at-sea incineration of Shell wastes indicate solid deposits were formed on the tips of the burners and sides of incinerator walls [14]. However, it was estimated that the amounts of solid residues formed were small in relation to the total mass of combustion products [14]. Furthermore, data obtained during the land-based incineration of nitrochlorobenzene (a liquid waste) indicate no ash formation, and apparently any solids produced leave the in incinerator as particulates entrained in the gas stream or as suspended solids in scrubber wastewater. Data are not available concerning gas stream particulate loading or suspended solids in scrubber water resulting from the burning of Shell wastes. Analysis of solid residues from the incineration of hexachlorocyclopentadiene (C-5,6) wastes showed mostly carbon (89-98%) and no measureable quantities of the waste [9].

Monitoring Equipment

Instrumentation capability of most incineration companies studied show measurements are made for all process parameters, including temperatures, pressures and flow rates. However, regulations currently in effect for facilities burning a specific organochlorine material (polychlorinated

biphenyls, PCBs, 40 CFR part 761) and regulations soon to be established as a part of RCRA include stipulations which will require additional continual and intermittent monitoring equipment [26,27]. PCB regulations were promulgated as a result of the Federal Toxic Substances Control Act (Public Law 94-469). These regulations stipulate that during initial use of an incinerator, and after any modification, the following constituents have to be monitored: O_2, CO, CO_2, NO_x, HCl, organic chlorides, PCB chemical substances and total particulates [26]. Continuous monitoring is required of O_2, CO and CO_2. Other performance standards are stipulated regarding temperature, residence time, combustion efficiency, maximum allowable stack emission (when incinerating non-liquid PCB wastes), and automatic cutoff systems for below optimal operation conditions [26].

RCRA was enacted to control the manner in which hazardous waste disposal facilities are operated, thus the incineration of organochlorine wastes will be subject to RCRA's regulations. The preliminary draft of RCRA regulations requires not only monitoring of various incinerator parameters (e.g., temperature, concentrations of O_2, CO_2 and O, etc.), but there are also requirements for the monitoring of ambient air (at the facility's perimeter), and scrubber water [27].

Methods of Storage and Transportation of Wastes and Residues

The manner in which a waste is handled on-site is dependent on plant design, plant storage facilities, and heat content of the fuel. Wastes received for incineration at a disposal facility are either incinerated directly (in some cases via pumping directly from the tank truck), or stored until they can be handled more conveniently. A plant operator may want to store some of the incoming wastes with higher heating values to possibly blend with other wastes which have heating values too low to support combustion alone.

Development of acceptable procedures for both storing and handling hazardous wastes has been mandated by RCRA and therefore, these processes will be regulated. The preliminary draft of RCRA regulations requires that wastes be stored in a manner which precludes discharge. There are also requirements for spill prevention and diking of storage areas in order to mitigate the effects of spills which may occur.

SIMULATION OF AIR QUALITY CHANGES: LAND-BASED INCINERATION

Gaussian diffusion and transport models were used to simulate the air quality changes expected as a result of land-based incineration activities. A detailed description of the simulation analysis is presented in Appendix B.

Air quality simulations were based on emissions and other data obtained at an incineration facility considered to be representative of a modern U.S. commercial disposal facility capable of accepting organochlorine wastes. The incineration system at this facility consists of a liquid injection burner and a rotary kiln both of which feed a common afterburner [11]. While the first of these burners is for liquids only, the rotary kiln is capable of burning liquids, sludges, and solids fed as fiber packs. The unit operates 24 hours per day, seven days per week, and it can achieve temperatures in excess of 1090°C (2000°F) and residence times between 2 and 3 seconds [11]. Combustion gases pass through the afterburner, a venturi scrubber system, and finally out a 30 meter (98 foot) stack to the atmosphere. The scrubber fluid is a 32% $Ca(OH)_2$ solution.

Under absolute optimal conditions, the feed rate to the two burners in the incinerator can reach 2840 liters per hour (750 gallons per hour). However, the typical average feed rate (which also takes into account normal maintenance downtime) is estimated to be about 2270 liters per hour (600 gallons per hour).

Data concerning the plant's operation and physical dimensions were used to derive effective stack height, an important input to air quality simulation models. These parameters included physical stack height (30 meters), stack diameter (2 meters), and operation data obtained during the incineration of nitrochlorobenzene wastes (an average stack velocity of 8.7 meters/sec, and temperature of exiting stack gases during waste incineration of 60°C). The derived effective stack height was 96.5 meters. The details of this calculation are presented in Appendix E.

The meterological inputs which were used in the air quality simulations were also considered to be representative of conditions at the hypothetical New Jersey site. Specific parameters used were a wind speed of 4.0 meters/second and a D Stability Category. As is common in air quality modeling, it

was assumed that pollutants remain airborne with no identifiable sinks at the ground level.

Air quality simulations were performed for four parameters: HCl, particulates, trace metals (Ti, Ni, and Cr) and unburned wastes. The emission estimates for the first three of these were obtained during the incineration of nitrochlorobenzene (NCB) wastes at the selected representative facility. The elemental composition of this compound is listed below:

	Weight Percent
Carbon	46.14
Hydrogen	2.80
Nitrogen	8.92
Chlorine	23.28
Sulfur	0.02

Due to the presence of significant quantities of nitrogen, NCB would not qualify as an organochlorine according to the definition previously given to this term. However, the NCB burn was the only source of available data that was potentially applicable to this analysis. It was also felt that the levels of selected emission constituents, (excluding those due to the nitrogen content), would generally be representative of organochlorine wastes at a modern disposal facility. For example, the HCl removal achieved by the scrubber at this facility (99.5% to 99.8%) is about the same as that required in draft RCRA regulations (>99%) [11,27]. Furthermore, tests at another facility indicate that even better removal efficiencies are obtainable [9]. These tests showed that HCl was undetectable in stack gases produced during the incineration of an organochlorine waste with a 62% chlorine content [9].

The emission rates for the unburned waste were determined artifically and based on the destruction efficiency achieved during the NCB burn. NCB constituents were not detected in the exiting combustion gas (0.05 mg/m^3 was the detection level); therefore, the calculated destruction efficiency is >99.999%. For the air simulation analysis, it was assumed that 0.01% of the waste feed was emitted as unburned wastes. The feed rate would be approximately 3 tonnes/hour, assuming that waste alone was being fed.

The emissions used in the air quality simulation are listed in Table 6. The results of the simulation are presented in Table 7. These results represent ground level concentrations expected to occur along the plume centerline. The data show that maximum concentrations are generally reached 3000 meters downwind of the source. The relatively high effective stack height generally precludes ground level effects from the plume within the first 300 to 400 meters from the source. In general, all of the simulated concentrations are low (none reach the $\mu g/m^3$ level) and would not be detectable by common analytical techniques. The maximum HCl concentration listed is equivalent to a value of 0.0004 ppm.

TABLE 6. STACK EMISSIONS USED FOR LAND-BASED AIR QUALITY SIMULATION

(All rates in kg/hr)

HCl	Particulates	Trace Metals, Each	Unburned Wastes
0.895	1.03	0.00069	0.3

Notes:
1. Emission rates for HCl, particulates, trace metals, and unburned wastes are all based on a dry volumetric flow rate of 68877 m^3/hr. Concentrations of HCl, particulate and trace metals in the stack gases are 13 mg/m^3, 15 mg/m^3 and 0.01 mg/m^3, respectively.
2. Trace metals include Ti, Ni and Cr, each at the listed concentration level. These concentrations are based on analysis of the waste and not on stack gas measurements.
3. Emission estimates for unburned wastes were based on a 99.99% destruction efficiency and a hypothetical waste feed rate of 3 tonnes/hr considered to be the average feed rate for Shell waste at one of the largest U.S. incinerators.

TABLE 7. RESULTS OF AIR QUALITY SIMULATION FOR LAND-BASED INCINERATION: HCl, TRACE METALS, UNBURNED WASTE AND PARTICULATES[a]

Distance Downwind From Facility (Meters)	GROUND LEVEL CONCENTRATION			
	HCl (ng/m^3)	Trace Metals (Ti,Ni & Cr,ea) (ng/m^3)	Unburned Waste (ng/m^3)	Particulates (ng/m^3)
100	.00	.00	.00	.00
200	.00	.00	.00	.00
300	.00	.00	.00	.00
400	.00	.00	.00	.00
500	.07	.00	.02	.08
600	2.88	.00	.96	3.31
700	9.20	.01	3.09	10.59
800	31.03	.02	10.40	35.71
900	57.47	.04	19.26	66.14
1000	148.08	.11	49.63	170.41
2000	477.06	.37	159.91	549.02
3000	536.61	.41	179.87	617.55
4000	489.52	.38	164.09	563.36
5000	425.73	.33	142.70	489.95
6000	367.13	.28	123.06	422.51
7000	317.79	.25	106.52	365.72
8000	277.36	.21	92.97	319.19
9000	244.06	.19	81.81	280.87
10000	216.52	.17	72.58	249.18
20000	90.42	.07	30.31	104.05
30000	51.90	.04	17.40	59.73

[a]Simulation parameters were: effective stack height = 96.5 meters, and wind speed = 4.0 meters/second.

SCRUBBER WATER CHARACTERIZATION

In this portion of the report, two different waste streams will be characterized. The streams are 1) the effluent resulting from single pass scrubbing; and 2) blowdown from recirculating scrubbers. No data were available to evaluate the composition of the wastewater effluence from HCl recovery processes discussed previously. However, it can be expected that the HCl recovery processes will have much lower TDS concentrations than systems which do not recovery HCl because a large proportion of the dissolved ions would be removed during recovery of the acid.

Analysis of the scrubber wastewater for undestroyed waste (organic content) showed no organic constituents present above detection levels which ranged from 0.1 to 0.5 ppm [11]. Detection levels range due to various types of organic analyses performed (i.e., gas chromatography, infrared spectrophotometry and low resolution mass spectrometry), interfering species in effluent analyzed and the organic component of the sample being detected. Analysis data that applied specifically to suspended solids in the scrubber water were not available.

Characteristics of Blowdown from Recirculating Scrubbers

Blowdown from recirculation systems occurs when the salinity reaches approximately 3 percent. This relates to a TDS value of 30,000 milligrams per liter [22]. The blowdown rate is variable, depending on the amount of chlorine in the liquid incinerated and on the liquid feed rate.

Characteristics of Single-Pass Scrubber Effluent

The characteristics of single-pass scrubber effluents are highly variable, depending on the chlorine content of the liquid incinerated, the liquid feed rates, the scrubber solution feed rates and the efficiency of the scrubber. Because single-pass systems have so many variables, it is not possible to obtain a normal or average TDS concentration. However, it is possible to estimate the magnitude of TDS concentration. This has been done by using two sets of data shown in Tables 8 and 9. The data were picked because their operating parameters produced two extremes in scrubber water quality, as shown in Table 9. Generally, scrubber wastewaters will contain TDS concentrations less than 40,000 milligrams per liter.

TABLE 8. SCRUBBER WATER AND WASTE PARAMETERS FOR TWO LAND-BASED LIQUID INJECTION INCINERATORS

	Waste Incinerated	
	Hexachlorocyclo-pentadiene[a]	Nitrochloro-benzene[b]
Fresh Scrubber Water Feed Rate (liters/min)	60	3200
Caustic Solution Feed Rate (liters/min)	23.8	8.5
Type of Solution Used	12% NaOH	32% $Ca(OH)_2$
Liquid Waste Feed Rate (kilograms/hr)	52.8	1893
Elemental Chlorine Content of the Waste	77%	10%

[a]Source: Reference 9
[b]Source: Reference 11

TABLE 9. RESULTS OF SCRUBBER WATER QUALITY CALCULATIONS

	Waste Incinerated	
	Hexachlorocyclo-pentadiene	Nitrochloro-benzene
Chlorides (milligrams/liter)	11,000	1,300
Calcium (milligrams/liter)	--	530
Sodium (milligrams/liter)	25,670	--
Total Dissolved Solids (milligrams/liter)	36,670	1,830

[a]Calculations are presented in Appendix C.

Handling of Scrubber Wastewater

Scrubbers used at facilities which incinerate organochlorine materials are designed to remove HCl and particulates that may be generated as combustion products. Therefore, treatment normally includes clarification (to remove particulates), neutralization (to take care of any residual acid or base that may still be present), and dilution (to help control TDS levels). Particulates which are insoluble in the scrubber fluid become suspended solids in the scrubber wastewater. If the particulates dissolve in the scrubber fluid, they contribute to the wastewater's TDS level. Suspended solids in scrubber wastewater generally present little, if any, problems because their concentrations are usually less than 5 mg/liter. Suspended solids are usually removed by on-site settling ponds.

Wastewater with either high or low pH levels must be neutralized prior to final discharge (to a municipal sewer, or receiving stream). This is usually accomplished by adding either acid or base.

The high concentration of total dissolved solids (due to NaCl, $CaCl_2$ and in some cases the excess NaOH not used to neutralize HCl) must be reduced. This is usually accomplished by piping scrubber effluents to in-plant treatment systems or by diluting with other plant process streams and storing in a holding pond or lagoon.

In geographical locations with high evapotranspiration rates, solar evaporation could be used as a method for disposing of scrubber wastewater. For such a method to be considered environmentally acceptable, the scrubber wastewater would have to be devoid of potentially volatile materials which are hazardous. The ponds used for evaporation would have to be periodically drained, and the accumulated sludge removed.

Information contained in a draft position paper concerning RCRA indicates that EPA regulatory officials may consider residue resulting from the incineration of hazardous wastes as also being hazardous [28]. Moreover, preliminary drafts of RCRA's regulations state that one of the general guidelines of RCRA is that waste disposal activities should be performed in a manner which precludes discharges to the environment [27]. If these concepts and rules are implemented within the regulatory controls required by RCRA, significant

restrictions will be imposed on the manner in which scrubber wastewater is handled. Three stipulations from the draft RCRA regulations indicate that such restrictions may indeed be imposed. These stipulations are (1) scrubber wastewater must be impounded prior to discharge or disposal, (2) releases must occur through a point source, and (3) discharge is to take place in a manner which allows for composite sampling for compliance testing. Thus, scrubber wastewater discharged to municipal sewers may be routinely sampled to insure that it doesn't contain unacceptable levels of unburned organochlorine wastes or toxic elements. Similarly, the sludges, or other sediments collected from settling ponds, evaporation ponds, or other types of lagoons may also contain unburned wastes or toxic trace elements (abstracted from the combustion gases as particulates, or formed as precipitates following chemical reactions occurring in the pond). These sludges will have to be disposed of in a manner consistent with the objectives of RCRA.

POTENTIAL FOR MALFUNCTION AND ACCIDENTS: LAND-BASED INCINERATORS

Categories of Failure Modes - General

Incineration process failure events, for the purpose of environmental consideration, are critial when degraded performance or accidental release of hazardous materials occur. An accidental shutdown, without any polluting consequence, is a failure event that results only in an increased cost of operation.

It is well known that industrial equipment malfunctions are only partially caused by mechanical or material failures. The other chief contributor to faulty operations comes from people problems, either through operator errors and negligence, vandalism, or deliberate violation of operating policies and legal constraints. The possibility of any of these malfunction causes occuring has been included in the subsequent analyses.

Incineration Facility Configuration

The functional diagram of an incineration faciltiy, shown in Figure 5 for a land-based operation, indicates that most components of the system are in a "series" configuration; each series component must be adequately functioning to avoid degraded performance. A few process components may be in a "parallel" configuration allowing a switchover to another component when problems are detected with the on-stream component. Waste feed line filters will usually have two or more units in parallel, and even feed pumps may be "spared" (duplicated) if plant processing rates are determined to be especially critical. Multiple burners in an incinerator are not considered to be redundant components because the loss of any burner will result in degraded performance.

Failure Mode Analysis

A detailed breakdown of potential malfunctions and accidents at each process element is shown in Table 10. The likelihood of any of these malfunctions occuring is very difficult to estimate in most cases, except for some estimates of industrial equipment on-stream time that have been developed from substantial statistical reports [29, 30, 31]. The likelihood

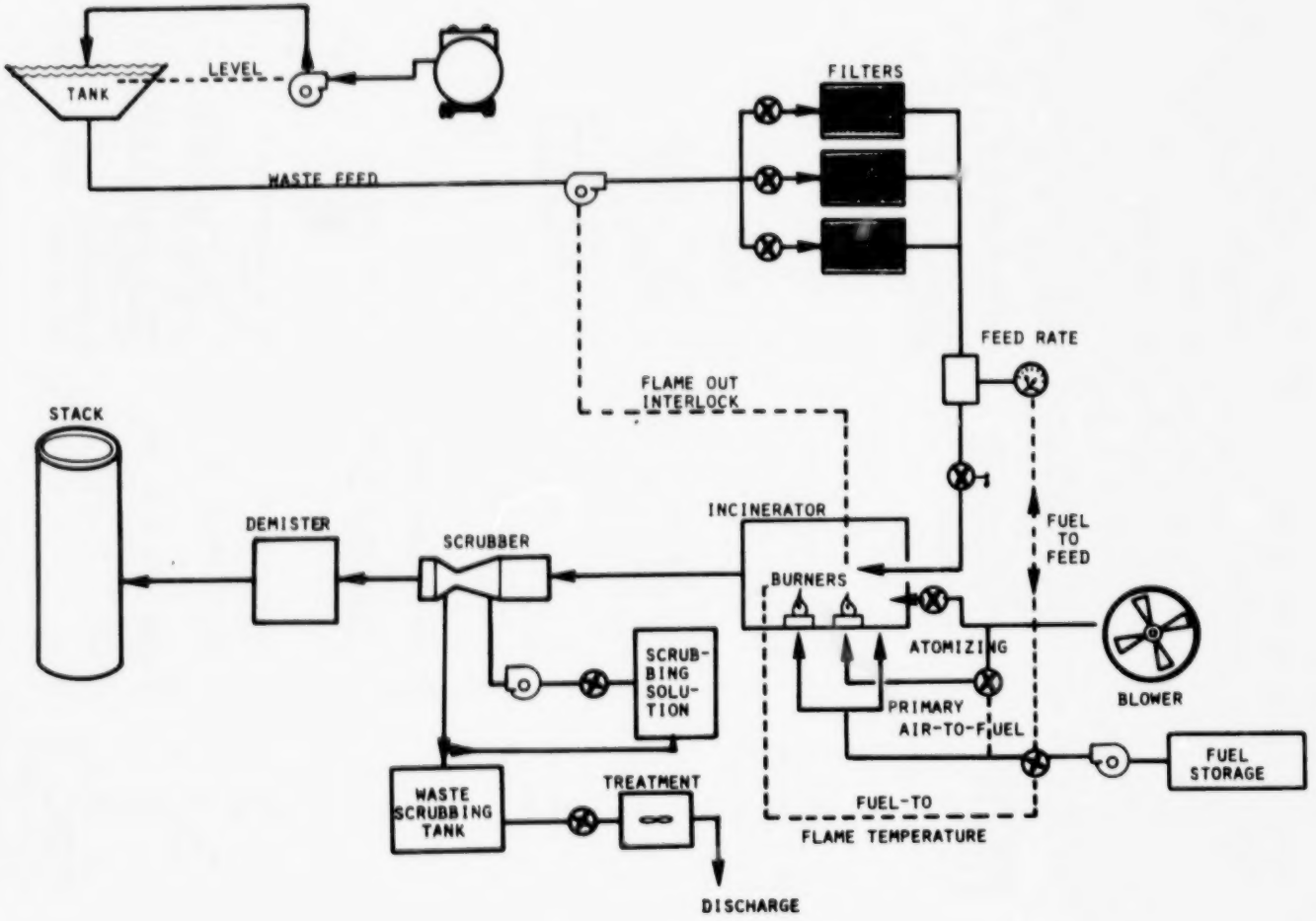
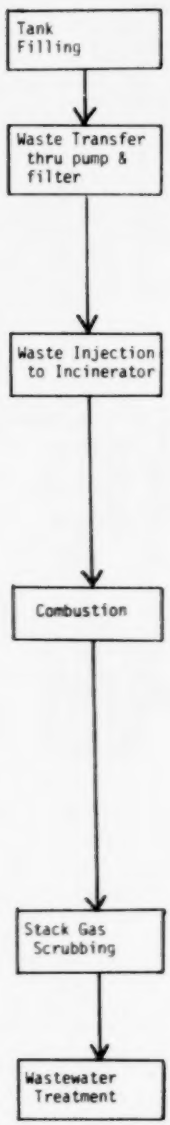


Figure 5. Liquid waste incinerator schematic.

TABLE 10. INCINERATION PROCESS FAILURE MODE ANALYSIS: LAND-BASED FACILITY



PROCESS ELEMENT	FAILURE CAUSES	CONSEQUENCE
Tank Filling	- Overfill on level interlock failure	Waste spill
	- Leakage due to pump seal, valve packing material corrosion, etc.	Small waste spill
	- Inclusion of unauthorized waste by subversion of quality control procedures	Possible incineration difficulties
Waste Transfer thru pump & filter	- Leakage due to pump seal, material corrosion, etc.	Small waste spill
	- Filter plugging	None if filters switched on high pump discharge pressure measurement
Waste Injection to Incinerator	- Nozzle plugging (low flow detection)	Temporary shutdown
	- Atomization air loss on air blower failure	Failure to combust, toxic vapor discharge, liquid accumulation
Combustion	- Burner flame loss (flameout) due to loss of fuel pressure, loss of primary combustion air, coking, or water slug in feed	Transient toxic vapor discharge prior to automatic shutdown (due to flame loss detection or low combustion temperature). (A water layer in the tank can be isolated by conductivity measurement and interlocked with the waste feed pump.)
	- Improper fuel rate	Excess waste product in discharge.
	- Improper air/fuel ratio	Inefficient combustion
	- Injection into a cool combustion zone on startup	Inefficient combustion
Stack Gas Scrubbing	- Scrubbing solution circulating pump fails	High HCl concentration in stack gases
	- Weak scrubbing solution	Not much change; even water scrubbing is very effective for HCl removal
	- Pump, valve, or tank leaks	Scrubbing solution spill (no consequence if water is used for scrubbing)
Wastewater Treatment	- Chemical addition pump fails	Low pH discharge
	- Pump, valve, or tank leaks	Small wastewater spill

of vandalism, in particular, is difficult to estimate because vandalism at industrial facilities is very infrequent when normal security precautions are taken. When security is lax, however, the results of vandalism can be very serious. A recent example of this is the vandalism of waste storage tanks at a North Carolina facility, in which the contents of the tanks were drained into the city water supply. Furthermore, unattended equipment in the field may be subject to theft, rifle shootings, and other damage possibilities.

In addition to potential problems listed in Table 10, there are a variety of operation practices which may also result in adverse environmental impacts, or damage incidents. An example would include the use of unlined ponds as a storage facility for wastewater streams which could contain constituents of the waste. Soluble constituents may be leached from solids in the wastewater and find their way to groundwater. Pond overflow could occur during heavy rainstorms and result in the introduction of waste constituents into the surface water streams.

Countermeasures and Contigency Planning

The largest hazardous spill possibility at a land-based facility exists in the storage tank and transfer area. This entire area should be paved, diked, and drained to a catch basin with pumped return to the storage tanks. Absorbent material should be ready to use for cleanup in the event of a leak or failure in other parts of the system. Each facility must be well-regulated and have contingency plans specifying requirements and fail safe devices to minimize the effects of a failure.

The extent to which any of the potential problems identified in prior discussions become real world problems will be significantly influenced by regulations expected to be established as a result of RCRA. The legislation and its regulations were initiated partly in response to problems and damage incidents resulting from accidents and improper disposal practices. Thus, it is reasonable to expect regulations ultimately promulgated pursuant to RCRA will be directed at preventing situations which caused problems in the past. Draft regulations which respond to RCRA's Section 3004 ("Standards Applicable to Owners and Operators of Hazardous Waste Treatment, Storage and Disposal Facilities" provide

specific mandatory provisions and procedural guidelines for the manner in which hazardous waste incinerators, and other types of disposal facilities should be operated. The aim of these provisions and guidelines is to preclude the kinds of incidents which could lead to adverse effects on public health and/or the environment. In addition, the draft regulations contain sections which cover "Emergency Procedures and Contigency Plans" and "Security". The requirements within these sections deal specifically with potential problem areas discussed previously. If new problem areas arise which are not covered by promulgated RCRA regulations, provisions within RCRA and its regulations allow for the establishment of new regulations and/or permit requirements.

DISCUSSION OF ENVIRONMENTAL IMPACTS FOR LAND-BASED INCINERATION

Table 11 summarizes the major air and water impacts that may result from land-based incineration. Generally, all concentrations appear to be low with respect to those necessary to cause immediate adverse impacts. The maximum HCl concentration is 536.6 nanograms/cubic meter or 0.0004 ppm. This is approximately four orders of magnitude less than the TLV of 5 ppm. This concentration is also lower than the sensory threshold levels reported in the literature, and also below any known effect level [32]. The most stringent of the National Ambient Air Quality Standards (NAAQS) for particulates (60 $\mu g/m^3$ - annual geometric mean) is an order of magnitude larger than the maximum predicted particulate concentration. It should also be stressed that tests showed no emission of unburned wastes from the stack, and the emissions rate used in the model was based on a 99.99% DE, while the calculated DE was 99.999%. Therefore, the predicted concentrations of unburned wastes are conservative.

Water quality impacts will be reflected in the need for additional downstream treatment and in possible adverse effects of heavy metals and high TDS. These adverse effects include direct impacts on treatment plant processes (e.g., process upsets and/or receiving water bodies if these materials were not removed by the treatment process) and indirect effects of any trace metals or unburned waste that might be associated with the sludges resulting from treatment.

All effluent streams (stack gas, spent scrubbing solution, sludge, clinker, bottom ash, and treated scrubbing solution) have the potential of adversely affecting the soil. Impacts on the soil can be manifested in several ways, ranging from no adverse effects to contamination of the soil, vegetation, and groundwater.

The combustion products which are entrained in the stack will eventually be removed from the atmosphere, as previously discussed, and will come into contact with the soil or surface water. The effects and interactions of these contaminants with surface water have been previously discussed, and their interaction with the soil will be addressed in the discussion of residue handling.

TABLE 11. SUMMARY OF AIR AND WATER QUALITY EFFECTS ASSOCIATED WITH LAND-BASED INCINERATION

AIR QUALITY[a] (ng/m^3)				SCRUBBER WATER QUALITY[b] (mg/liter)							
				WASTES W/77% Cl CONTENT[c]				WASTES W/10% Cl CONTENT[d]			
HCl	Particulates	Unburned Wastes	Trace Metals	Cl^-	Ca^+	Na^+	TDS	Cl^-	Ca^+	Na^+	TDS
536.6	617.6	<179.9	<0.41	1100	-	25,670	36,670	1300	530	-	1830

a) Maxima from air quality simulations: effective stack height = 96.5 meters, wind speed = 4.0 meters/second, and atmospheric stability category = D. These maxima occur 3000 meters downwind from the position of the source.

b) TDS levels of scrubber water depend primarily on percentage chlorine composition of the incoming wastes and type of scrubber solution used. Concentrations in mg/liter.

c) Scrubber solution is 12% NaOH.

d) Scrubber solution is 32% $Ca(OH)_2$.

Clinker and any bottom ash formed will contain primarily inorganic and carbonaceous compounds. Less than 3% of the total weight of carbonaceous compounds will be trace compounds, including heavy metals. Because of the presence of these heavy metals, these solids should be disposed of in landfills approved for hazardous wastes.

The spent scrubbing solution, if sent to an on-site settling tank or pond, will generate two streams. One stream will be the clear liquid effluent which may be suitable for sending to municipal treatment facilities. The other stream will be sludge or solid residue from the settling process, which, because it will contain heavy metals and perhaps some organics, should be disposed of in an approved landfill.

The spent scrubber solution may not be treated on-site, but rather disposed of directly into the municipal sewage system. The results of this will be that the sludges generated by the municipal treatment process will contain heavy metal contaminants which will be landfilled and, depending on the destruction efficiency of the incinerator, the liquid effluents could potentially contain small amounts of organochlorine wastes. However, if DEs are kept at the levels achieved on test burns, (it is expected that regulatory controls will insure that is the case), no unburned wastes will be expected in the scrubber wastewater.

The effects of the contaminants once deposited onto or into the soil vary as a function of the type and porosity of the soil, the weather conditions and the mobility of the individual contaminants [33]. For example, cyanide (CN^-) and selenium ($HSeO_4^-$ and $SeO_3^=$) are relatively mobile in the soil, while metal cations, such as iron (Fe^{++}), zinc (Zn^{++}), lead (Pb^{++}), copper (Cu^{++}) and beryllium (Be^{++}) are less mobile in the soil [33].

The effects of the hydrocarbon-associated sediment are a function of the depth of the sedimentation layers. Hydrocarbons in surface sediments near outfalls will closely resemble the original suspended solids. Once incorporated into the sediment, microbial decay will occur, leaving cycloparaffins and other aromatics to predominate at depths close to 50 centimeters [34].

The magnitude of any of these effects cannot be determined accurately using available data. If the concentration of heavy metals and unburned wastes in waste scrubber water is found to be too high, then additional treatment may be required. If these high concentrations are found in wastewater treatment sludges, then the chosen disposal method for the solids will have to insure that air and water resources are not contaminated.

RCRA required that the Administrator of the Environmental Protection Agency promulgate standards applicable to hazardous treament, storage, and disposal facilities. These standards include requirements for operating methods, and practices, location and design of facilities, and contingency plans for minimizing unanticipated damage from treatment, storage, or disposal of hazardous waste. These regulations, along with the existing PCB regulations, will have a major effect on insuring that the incineration of organochlorine wastes at land-based facilities will proceed in an environmentally acceptable manner.

SECTION 4

AT-SEA ALTERNATIVE

GENERAL DESCRIPTION

Recently, at-sea incineration has been carried out in three ships, the Matthias II, the Matthias III and the M/T Vulcanus. Matthias II is a vessel of 1000 deadweight tons and operated primarily in Europe. Matthias III is a modified tanker of 19,300 dead weight tons and was built to burn both liquids and solids. However, it was only used for a short time and is currently out of service because it did not perform satisfactorily.

The M/T Vulcanus burns only liquid wastes and is a double-hull, double-bottom vessel that meets all applicable requirements of the Intergovernmental Maritime Consultative Organization (IMCO) concerning transport of dangerous cargo by tanker. Before being permitted to operate in U.S. waters, it was modified to meet requirements of the U.S. Coast Guard. Originally a cargo ship, it was converted to its present use in 1972. Its size--an overall length of 102 meters, a beam of 14.4 meters, and a maximum draft of 7.4 meters--enables it to operate worldwide. It is also able to operate in rough weather. The crew numbers 18, 12 to operate the vessel and six solely to operate the incinerators. Two diesel engines drive the single propeller to give cruising speeds of 10 to 13 knots. The waste is carried in 15 tanks, the walls and bottoms of which form the inner hull and bottom. The space between the two hulls is used for ballast. Ballast tanks may be filled with seawater and emptied independently as required to trim and balance the ship. The tanks range in size from 115 to 574 cubic meters, with an overall waste capacity of 3503 cubic meters. Tanks are filled through a manifold on deck using a dockside loading pump. During normal operation, the waste tanks can be discharged only through the incinerator feed system. There is, however, provision for discharging the cargo into the ocean if an appropriate emergency arises.

Waste is burned on the M/T Vulcanus in two identical refractory lined furnaces located at the stern of the ship. Each incinerator consists of two main sections, a combustion chamber and a stack, through which the combustion gases pass sequentially. Air for the combustion is supplied by large fixed speed blowers rated at 90,000 cubic meters/hour capacity for each incinerator. Liquid wastes are fed to the incinerator by means of electrically driven pumps. There are no air pollution control devices on the incinerators, but there is an emergency automatic waste shutoff system which prohibits the flow of waste to the burners if the furnace temperature drops below a preselected level.

SIMULATION OF AIR QUALITY CHANGES FOR AT-SEA INCINERATION

Gaussian diffusion and transport models were used to simulate the air quality changes expected as a result of at-sea incineration activities. A detailed description of the simulation analysis is presented in Appendix B.

As explained in Appendix B, simulations were based on a set of meteorological and other conditions considered to be generally representative of those likely to occur under real world circumstances. The calculation of effective stack height (an important input parameter for diffusion models) was based on data obtained on the M/T Vulcanus during the March 1977 burn. The wind speed and atmospheric stability category used were selected after review of measured and statistical data for shore locations in the general vicinity of the proposed North Atlantic burn zone. (Measured wind speed data are not available for the proposed off-shore site, therefore, data from the nearest shore-based meteorological stations were used instead.)

Wind speed (i.e., speed of the diffusing layer) is an input parameter which significantly influences predicted downwind pollutant concentrations. (Generally, increasing wing speed decreased downwind concentration.) When an incinerator ship is moving, the relative wind speed, as measured at the stack, may be greater than the speed of the diffusing layer. However, relative wind speed was not used as an input to the diffusion modeling performed here. This is because the materials emitted from the stack will assume the average speed of the diffusing layer shortly after they are discharged to the atmosphere. One result of this is that downwind concentrations near the source may be lower (due to the additional mechanical turbulence from the

ship's velocity) than estimated in this study. Downwind concentrations will also tend to be decreased by the fact that a moving source distributes its emissions into a larger volume of air per unit time (i.e., if the relative wind speed is greater than that of the diffusing layer).

The diffusion model employed in the air quality simulation assumed perfect reflectivity and conservation of pollutants in the diffusing layer. That is, it is assumed that the chemical species emitted remain airborne and are not abstracted from the atmosphere by either chemical or physical processes. There are a variety of technical arguments against this assumption. However, there is no technique available which takes pollutant-marine boundry layer interactions into account for the type of air quality simulation being performed here.

The emissions rate used for the air quality simulation is based on test data from the March 1977 Gulf of Mexico cruise of the M/T Vulcanus. The wastes burned were produced during the manufacture of allyl chloride, epichlorohydrin, dichloroethane, and vinyl chloride by the Shell Chemical Company. They were stored at the Shell Company's Deer Park, Texas plant, near Houston. Composition of the waste is given in Table 12. Elemental analysis of a typical organochlorine waste is shown in Table 13. This waste shown was incinerated in the Gulf of Mexico during two burns in 1974, and is similar in composition to the waste incinerated during the March 1977 burn.

Emission rates used for the at-sea incineration are shown in Tables 14 and 15. These estimates were made assuming feed rates and emissions characteristics of the M/T Vulcanus furnaces. Emissions data for particulates were not obtained during the March 1977 burn. However, data were available describing waste compostion and emissions of various inorganic constituents of the waste. These data were converted to mass emission rates and summed in order to derive an estimate of expected particulate emission.

TABLE 12. ANALYSIS OF ORGANOCHLORINE WASTE BURNED AT-SEA ("SHELL WASTE")

- Physical Characteristics:

Loss on ignition	99.8%
Gross Thermal Content	6,950 Btu/lb
Specific Gravity	1.28

- Elemental Analysis:

Element	Composition, %
Carbon	30.01
Hydrogen	4.17
Nitrogen	0.012
Sulfur	0.009
Halogens as chlorine	62.60

- Other Minor Constituents

Element	Concentration, ppm
Si	>500
P	50 - 500
Ti	50 - 500
Ca	<25
Br	Trace

- Organic Composition:

Compound	Est. Conc. (% w/w)
1,2,3-Trichloropropane	18
Dichloropropenes (3)	11
Dichloropropane	18
Trichloroethane	12
1,2-Dichloroethane	10
1,1-Dichloroethane	0.9
Dichloropropanol	6.2
Chloropropene (Allyl Chloride)	5.7
Chloropropanes (2)	5.8
Chloroethane	0.6
Trichloromethane (Chloroform)	0.5
Tetrachlorobutenes (2)	2.4
Acrolein (Propenal)	0.2
Chlorobenzene	3.3
Bis(2-Chloroethylether)	1.9
Unidentified Chloro-and Oxychloro-Compounds	3
Water	0.5

Source: Reference [10]

TABLE 13. ELEMENTAL ANALYSIS OF SHELL WASTE

	BURN I	BURN II
	% by weight	
Carbon	29	29.3
Hydrogen	4	4.1
Oxygen	4	3.7
Chlorine	63	63.5
	(parts per million)	
Copper	0.51	1.1
Chromium	0.33	0.1
Nickel	0.25	0.3
Zinc	0.14	0.3
Lead	0.05	0.06
Cadmium	0.0014	0.001
Arsenic	<0.01	< 0.01
Mercury	<0.001	<0.002

Source: Reference 17

TABLE 14. EMISSION RATES USED FOR AT-SEA AIR QUALITY SIMULATION : HCl AND UNBURNED WASTES

Average Waste Feed Rate	Destruction Efficiencies	Emissions Rate	
		HCl	Unburned Wastes
22 tonnes/hr ($22X10^6$gm/hr)	99.99% (max observed)	$14.16X10^6$gm/hr	$2.2X10^3$gm/hr
	99.96% (min observed)	$14.16X10^6$gm/hr	$8.8X10^3$gm/hr

Notes: 1) Data are for both furnaces of the M/T Vulcanus.

2) HCl emission rate assumes a 62.6% chlorine content in the waste, and a volumetric flow rate of 8700 Nm^3/hr of HCl is discharged from both stacks.

The "summed inorganics" column of Table 15 presents the results of this derivation. It should be noted that these results compare favorable with laboratory analysis data indicated 0.2% of a Shell waste sample remained as residue following ignition and combustion.

Air quality simulation results for at-sea incineration activities are presented in Tables 16 and 17. The listed concentrations correspond to the following set of conditions: an effective stack height of 125.5 meters, a wind speed of 4.0 meters/second, and a D (neutral) stability category. Under these conditions, maximum ground-level concentrations for plume constituents are predicted to occur 4000 meters downwind from the source.

The predicted concentration for HCl never reach the threshold limit value (TLV) of 5 mg/m^3 considered to be safe for 8-hour occupational exposure. Maximum expected concentration for HCl is 4.4 mg/m^3. Maximum concentrations predicted for all other constituents vary from a high of 2.4 $\mu g/m^3$ (for unburned wastes, assuming the minimum measured DE) to a low of 31 nanograms/m^3 (for arsenic and cobalt, each).

TABLE 15. EMISSION RATES USED FOR AT-SEA AIR QUALITY SIMULATION: INORGANICS

(All units in kg/hr)

Summed Inorganics		Specific Elemental Constituents					
Low	High	Cu/Zn	As/Co	Pb/Ti	Ni	Cr	F
53	72	0.7	0.1	0.4	2	4	1

Notes: 1) Data are for both furnaces of the M/T Vulcanus

2) Data on the concentration ranges of inorganics in the wastes and in stack emissions were collected and converted to mass emission rates. These rates were summed for all inorganics, and are considered to represent estimates of expected particulate emissions for the at-sea incineration of Shell wastes.

3) When two elements are listed, the noted emission rates are for <u>each</u> constituent.

TABLE 16. RESULTS OF AIR QUALITY SIMULATION FOR AT-SEA INCINERATION: HCl, UNBURNED WASTES AND INORGANICS.[a]

Distance Downwind From Ship (Meters)	HCl ($\mu g/m^3$)	GROUND LEVEL CONCENTRATION			
		Unburned Wastes ($\mu g/m^3$)		Inorganics ($\mu g/m^3$)	
		99.96% DE[b]	99.99% DE[b]	High	Low
100	.00	.00	.00	.00	.00
200	.00	.00	.00	.00	.00
300	.00	.00	.00	.00	.00
400	.00	.00	.00	.00	.00
500	.00	.00	.00	.00	.00
600	.10	.06	.00	.00	.00
700	.84	0.00	.00	.00	.00
800	8.09	0.01	.00	.04	.03
900	25.43	0.02	.00	.13	.10
1000	144.67	0.09	.02	.74	.54
2000	2082.66	1.29	.32	10.59	7.80
3000	2849.86	2.39	.60	19.58	14.41
4000	4422.80	2.75	.69	22.49	16.55
5000	4389.32	2.73	.68	22.32	16.43
6000	4116.79	2.56	.64	20.93	15.41
7000	3777.38	2.35	.59	19.21	14.14
8000	3438.65	2.14	.53	17.48	12.87
9000	3124.50	1.94	.49	15.89	11.69
10000	2843.01	1.77	.44	14.46	10.64
20000	1318.93	0.82	.20	6.71	4.94
30000	781.14	0.49	.12	3.97	2.92

[a]Simulation parameters were: effective stack height = 125.5 meters, wind speed = 4.0 meters/seconds, and stability category = D (neutral).

[b]DE = Destruction efficiency.

TABLE 17. RESULTS OF AIR QUALITY SIMULATION FOR AT-SEA INCINERATION: SELECTED TRACE ELEMENTS[a]

Downwind Distance From Ship (Meters)	Ground Level Concentration		
	F (ng/m^3)	Cu/Zn (ng/m^3)	Pb/Ti (ng/m^3)
100	.00	.00	.00
200	.00	.00	.00
300	.00	.00	.00
400	.00	.00	.00
500	.00	.00	.00
600	.01	.01	.00
700	.06	.04	.02
800	.57	.40	.23
900	1.80	1.26	.72
1000	10.22	7.15	4.09
2000	147.08	102.96	58.83
3000	271.08	190.32	108.75
4000	312.34	218.64	124.94
5000	309.98	216.99	123.99
6000	290.73	203.51	116.29
7000	266.76	186.73	106.71
8000	242.84	169.99	97.14
9000	220.66	154.46	88.26
10000	200.78	140.54	80.31
20000	93.14	65.20	37.26
30000	55.17	38.62	22.07

[a]Simulation parameters were: effective stack height = 125.5 meters, wind speed = 4.0 meters/second, and stability category = D (neutral).

TABLE 17. RESULTS OF AIR QUALITY SIMULATION FOR AT-SEA INCINERATION: (continued) SELECTED TRACE ELEMENTS[a]

Downwind Distance From Ship (Meters)	Ground Level Concentration		
	As/Co (ng/m^3)	Cr (ng/m^3)	Ni (ng/m^3)
100	0.00	0.00	0.00
200	0.00	0.00	0.00
300	0.00	0.00	0.00
400	0.00	0.00	0.00
500	0.00	0.00	0.00
600	0.00	.03	.01
700	0.00	.24	.12
800	.06	2.28	1.14
900	.18	7.18	3.59
1000	1.02	40.87	20.43
2000	14.71	588.32	294.16
3000	27.19	1087.53	543.77
4000	31.24	1249.38	624.69
5000	31.00	1239.92	619.96
6000	29.07	1162.93	581.47
7000	26.68	1067.06	533.53
8000	24.28	971.37	485.68
9000	22.06	882.63	441.31
10000	20.08	803.11	401.56
20000	9.32	372.58	186.29
30000	5.52	220.66	110.33

[a]Simulation parameters were: effective stack height - 125.5 meters, wind speed = 4.0 meters/second, and stability category = D (neutral).

WATER QUALITY CHANGES ASSOCIATED WITH AT-SEA INCINERATION

Parameters affecting the impact of at-sea incineration of organochlorine wastes on the ocean environment are listed below:

Completeness of combustion and destruction
Feed rate of organochlorine wastes
Waste composition
Plume behavior

Products of combustion (i.e., HCl and small amounts of unburned waste and inorganics that may be present) can reach the ocean only via the plume. The plume model which has been developed describes the behavior of a typical plume from a source such as the M/T Vulcanus.

The composition of the emissions which form the plume reflect the composition of the waste. The concentration of materials in the plume is dependent on the waste feed rate, the amount of air available to the combustion process, overall destruction efficiency, and the atmospheric conditions which are found over the burn area.

Atmospheric conditions over the ocean are generally stable so that the plume behavior is often consistent and can be reasonably predicted by a model. It is generally agreed that under stable conditions the plume tends to expand regularly and remain above the surface of the ocean for up to 60 km from the source. Such a situation is designated "coning aloft."

However, as a result of direct observations during at-sea incinerations in the North Sea, the Gulf of Mexico, and the South Pacific, additional parameters have been found to be important in plume behavior. These include the wind speed (relative to the speed of the ship) and the attitude of the ship with respect to the wind direction. These parameters exert effects on the plume which appear to be due to the turbulence or aerodynamic downwash produced by the superstructure of the ship. The result is impingement by the plume on the ship or on the ocean near the ship.

In the plume behavior model used in this discussion, HCl produced during the combustion of the organochlorine waste is used as a "tracer" for the plume. It should be understood that the plume contains other gases, principally H_2O and CO_2, with minor amounts of NO_x, CO, unburned waste, and salts of trace metallic constituents present in the waste.

Under the conditions of at-sea incineration used in this discussion, the weight ratio of HCl to unburned waste varies from 1200:1 (DE = 99.96%) to 6400:1 (DE = 99.99%). Whatever unburned waste enters the ocean from the plume, therefore, can be estimated from the HCl content of the plume. On the other hand, the concentration of inorganic material in the plume is directly proportional to the amount in the original waste, and is not affected by destruction efficiency. It is, however, affected by the amount of combustion air and, of course, by the behavior of the plume itself.

The model used to estimate expected seawater concentrations of plume constituents released during at-sea incineration is presented in Appendix D. Illustrative examples using the model are also presented in Appendix D. It should be noted that the model is conservative in that it assumes that 100% of the emitted plume constituents dissolve in a specified body of ocean water. Under real-world conditions, the "coning aloft" mode of plume behavior is more typical. Therefore, a sizable portion of the plume constituents will remain airborne for significant distances downwind. These constituents would not interact with the ocean water in the near vicinity to the source, and if interaction does take place downwind, the concentration of the constituent would be at much decreased levels. The illustrative examples presented in Appendix D show that, assuming a mixing depth of 20 meters (in accordance with the initial mixing criteria for ocean dumping regulations [7]), the seawater concentration for unburned waste is expected to be 92×10^{-3} ppb. The corresponding concentration for HCl would be 0.197 ppm. This calculated concentration neglects the fact that ocean water is a highly buffered, slightly alkaline fluid, and therefore, would rapidly neutralize HCl contributed by the plume. Consequently, an overall HCl concentration increase of 0.2 ppm would not be detected, via a pH change in seawater, and an 0.2 ppm increase in chlorine ion would be negligible compared with the 19,000 ppm chloride background of the ocean.

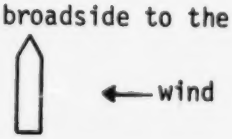
Furthermore, for a constituent that was in the waste at a concentration of 1000 ppm (0.1%), the resulting seawater concentration would be 0.39 ppb. (Analysis of waste similar to that incinerated during the March burn shows that copper was the most abundant trace metal, and the highest concentration measured in the waste was 1.1 ppm, three orders of magnitude smaller than the 1000 ppm used in the above calculation.) Thus, based on the model and the general composition of the wastes burned in the Gulf of Mexico, the seawater quality changes that can be attributed to at-sea incineration activities are on the order of fractions of ppb.

The intensity of the effect that at-sea incineration would have on ocean water quality is significantly influenced by plume behavior. From plume dynamics, one can draw conclusions about plume behavior at various ship attitudes. In the burn zone, it is often necessary for the ship to maneuver so as to remain within the prescribed boundaries, or to drive in a given direction with respect to the wind in order to avoid plume impingement on the decks. Furthermore, drifitng broadside to the wind is sometimes desirable when the weather is appropriate, because it saves fuel and conserves the ship's position within the burn zone.

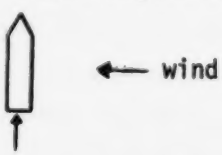
Three basic attitudes of the ship have been considered. These are:

1) Ship driving directly into the wind

2) Ship drifting broadside to the wind



3) Ship driving at right angles to the wind



Experience has shown that these three sets of conditions can affect the concentrations in the plume, and may even force the plume down onto the ocean or onto the ship.

The three basic attitudes of the ship are arranged below in order of decreasing severity of impact on the water quality. The effects differ slightly depending on whether plume touchdown occurs close to or far from the ship. For plume touchdowns close to the ship, water quality impact severity is in the following decreasing order:

- Drifting broadside
- Driving directly into wind
- Moving at 90° to wind

For plume touchdown far from the ship, water quality impact severity assumes the following decreasing order:

- Driving directly into wind or drifting broadside (equal severity)
- Moving at 90° to wind

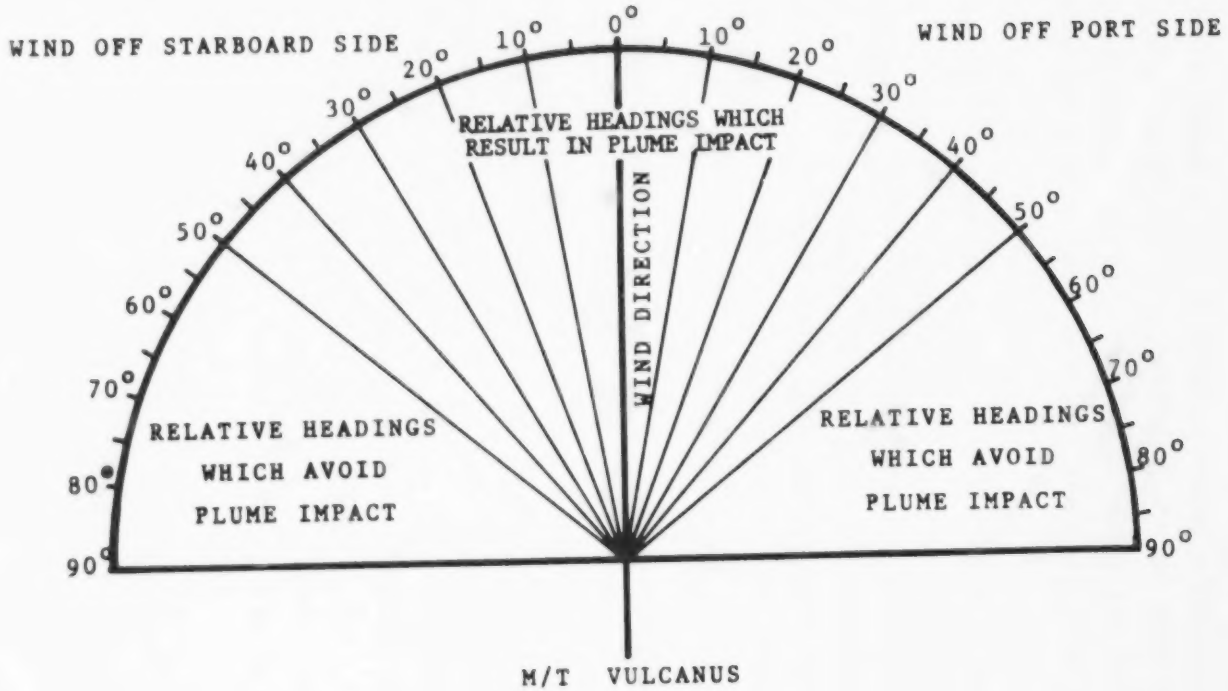
Although the best defined conditions are those of heading directly into the wind, there is enough evidence to validate the above generalizaitons.

During the at-sea incineration of organochlorine wastes by the M/T Vulcanus in the Gulf of Mexico [10], and more recently, in the Pacific [35] some experiments in plume control were undertaken. It was found that a ship's attitude closer than 50° to the wind resulted in the plume impingement, while taking the wind more directly toward the port or starboard beam moved the plume off the ship and onto the ocean.

Results are summarized in Table 18. Data were taken with a Drager apparatus, using a standard HCl measurement tube. From the table, a plot was made (Figure 6) which was used successfully by the personnel of the M/T Vulcanus to alter the ship's speed and direction so as to avoid plume impingement on the deck.

TABLE 18. HYDROGEN CHLORIDE (HCl) IN AIR ON BOARD M/T VULCANUS

DATE	TIME	LOCATION	RELATIVE HUMIDITY %	SHIP HEADING	WIND DIR. AND FORCE	TEMP °C/°F	BARO-METER (mb)	CONC. HCl (ppm)	NOTES
7-14-77	1600	Port, Comb Deck	84	340°	080°-8 m/s	27.2/81	1012.2	0	Drifting
	2000	Port, Main Deck	80	340°	060°-10 m/s	26.7/80	1012.2	0	Drifting
7-15-77	0800	Port, Comb.Deck	88	360°	100°-12 m/s	26.7/80	1012.5	2.0	Drifting
	1000	Port, Comb Deck	84	005°	100°-10 m/s	26.7/80	1012.5	0	Drifting
7-16-77	0800	Port, Comb Deck	88	348°	075°-8 m/s	26.1/79	1014.5	0	Drifting
	1600	Comb. Rm Foward	84	350°	060°-3 m/s	26.7/80	1013.8	0	Drifting
		Comb. Rm Rear	84	350°	060°-8 m/s	26.7/80	1013.8	0	Drifting
7-17-77	0940	Port, Main Deck	88	360°	065°-10 m/s	26.7/80	1014.8	0	Drifting
	1600	Port, Comb Deck	80	360°	070°-9 m/s	27.2/81	1013.0	0	Drifting
7-18-77	1020	Port, Main Deck	82	360°	090°-11 to 20 m/s	28.3/63	1014.0	0.5	Drifting
	1020	Comb. Room	82	360°	090°-11 to 20 m/s	28.3/83	1014.0	0.5-1.0	Drifting
	2030	Fantail	84	150°	105°-12 m/s	26.7/80	1014.5	2.0	40 RPM
	2040	Fantail	84	160°	106°-12 m/s	26.7/80	1014.5	0	40 RPM
	2400	Fantail	84	160°	100°-12 m/s	26.1/79	1014.5	0	40 RPM
7-19-77	1000	Fantail	82	045°	090°-16 m/s	27.2/81	1014.0	3.0	40 RPM
	1010	Fantail	82	035°	090°-16 m/s	27.2/81	1014.0	0	40 RPM
	1400	Fantail	78	040°	080°-12 m/s	27.5/81.5	1014.0	2.0	40 RPM
	1410	Fantail	78	030°	080°-12 m/s	27.5/81.5	1014.0	0	40 RPM
7-20-77	0800	Port, Main Deck	86	350°	080°-9 m/s	26.7/80	1015.3	0	Drifting
220	2200	Port, Main Deck	88	360°	085°-9 m/s	26.7/80	1014.9	0	Drifting
7-21-77	0800	Port, Comb Deck	86	350°	075°-8 m/s	26.7/80	1015.0	0	Drifting
	2000	Port, Comb Deck	82	345°	055°-9 m/s	26.9/80.5	1013.9	0	Drifting
7-22-77	0800	Port, Boat Deck	84	330°	050°-7 m/s	26.7/80	1014.5	0	Drifting
1800	1800	Port, Boat Deck	84	350°	060°-8 m/s	26.7/80	1013.0	0	Drifting
7-23-77	0800	Port, Comb Deck	84	005°	095°-8 m/s	26.7/80	1014.3	0	Drifting
	1800	Starboard, Comb Deck	84	140°	080°-6 m/s	26.7/80	1012.4	10.0	103 RPM
	1810	Starboard, Comb Deck	84	150°	080°-6 m/s	26.7/80	1012.4	2.0	103 RPM
	1820	Fantail	84	150°	080°-6 m/s	26.7/80	1012.4	0	103 RPM
	1830	Starboard, Comb Deck	84	155°	080°-6 m/s	26.7/80	1012.4	4.0	103 RPM
	1840	Starboard, Comb Deck	84	150°	080°-6 m/s	26.7/80	1012.4	0	75 RPM
	1850	Starboard, Comb Deck	84	150°	080°-6/m/s	26.7/80	1012.4	0	75 RPM
	1900	Starboard, Comb Deck	84	150°	080°-6 m/s	26.7/80	1012.4	0	75 RPM



CONDITIONS

- WIND SPEED 20 KT (10M/S)
- PROPELLER SPEED 40 RPM MAX.

Figure 6. Ship headings relative to wind direction which avoided plume impact on ship.

POTENTIAL FOR MALFUNCTIONS AND ACCIDENTS: AT-SEA INCINERATION

Categories of Failure Modes - General

From an environmental viewpoint, incineration equipment failure events are critical when degraded performance or accidental release of hazardous materials occur. An accidental shutdown, without any polluting consequence, is a failure event that only results in an increased cost of operation.

It is well-known that industrial equipment malfunctions are only partially caused by mechanical or material failures. The other chief contributor to faulty operations comes from people problems, either through operator errors and negligence, vandalism, or deliberate violation or operating policies and legal constraints. The possibility of any of these malfunction causes occurring has been included in the subsequent analyses.

Incineration Vessel Configuration

A functional schematic of the M/T Vulcanus at-sea incineration vessel is shown in Figure 7. Essentially, an incineration ship is a double-hulled vessel with under deck tankage forward for waste cargo; living, eating, sleeping, communications and ship navigation areas amidships; and a combustion area with associated controls and components (waste homogenizers, burners, automatic waste shutoff) at the stern. The pumps for the waste are located amidships below decks and beneath the living quarters; and the engine room is usually aft of the pump room and below decks. On upper deck space, above the living quarters and between the bridge and the incinerators are the blowers which supply the combustion air to the burners.

The waste handling and combustion operations are thus in-line functional processes, and, with the combustion air blower system, form the three principal unit operations of the at-sea incineration system.

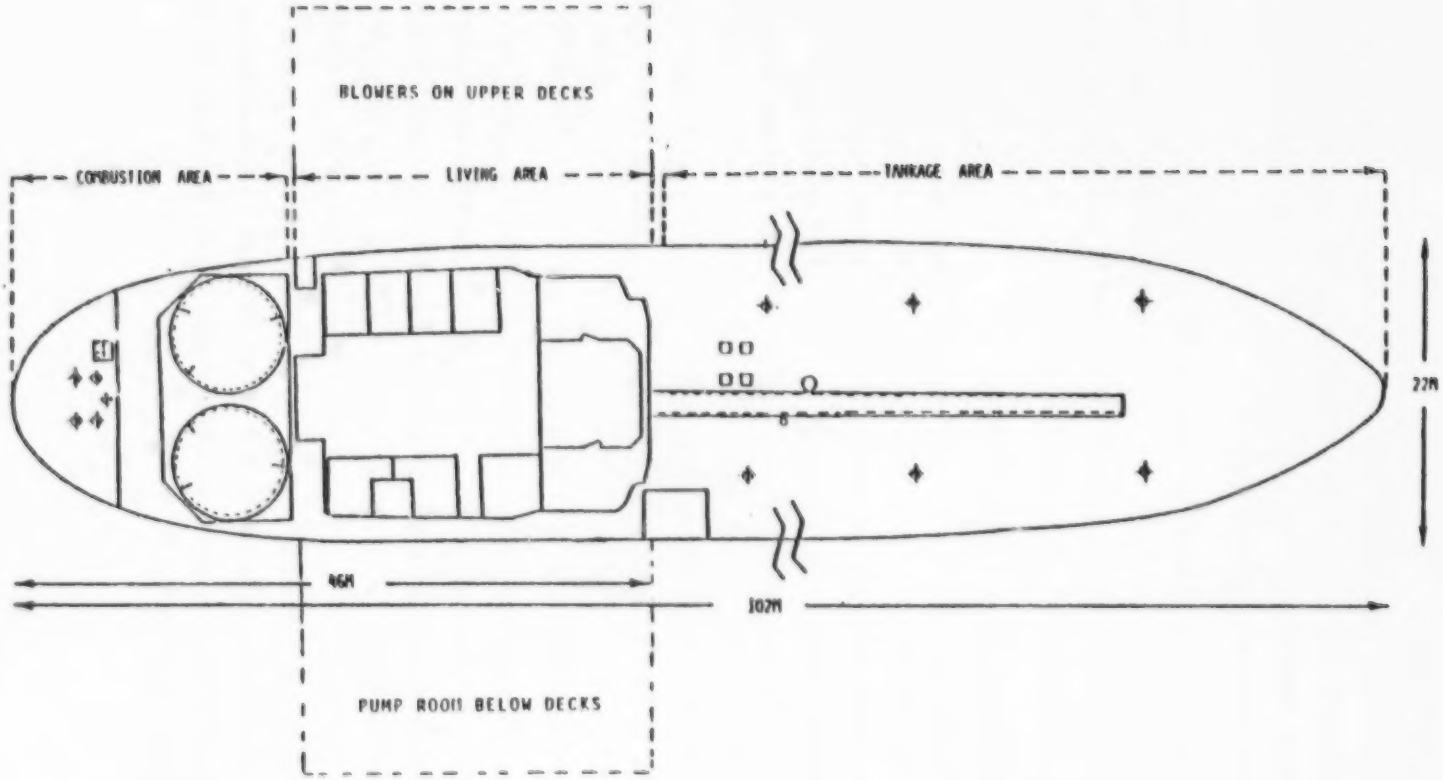


Figure 7. Locations of functional processes of the M/T Vulcanus

Failure Mode Analysis

Potential malfunctions and accidents are listed in Table 19. Estimates of the probability of these malfunctions occurring are subjective, except in the cases where statistical records of industrial equipment downtimes or fail rates are available [29,30,31].

Vandalism on an incineration ship is considered unlikely because the well-being of the crew is so closely tied to performance and safety. Moreover, opportunities and access to the operating equipment are not possible because of the confined nature of an incineration vessel.

Countermeasures and Contingency Planning

The greatest possibility of spills during an at-sea incineration operation is during loading. Hatches are open, samples are being taken, and exposed flex lines are under pressure. An additional source of contamination is the bilgewater associated with the room containing the pumps used for moving the organochlorine waste to the incinerator and between storage tanks. There are typically occasional leaks from these pump seals. Small but detectable amounts of the cargo wastes eventually find their way to bilge. Bilges should not be pumped into channels, at dock side or at sea. This would be a procedural violation. Provision must be made to dispose of the bilge, possibly through the incinerator, where it can be burned with fuel.

If flameout occurs as the result of a slug of noncombustible material (e.g., water) entering the waste feed lines and passing through one or more burners, subsequent incoming waste will be vaporized. Vaporization will occur due to the latent heat in the incinerator. This vapor will be emitted directly to the atmosphere. To prevent this failure mode, a positive and rapid waste feed shutoff system must be available. Such a system or device should rely on direct sensing of the burner flames (ultraviolet or infrared detectors) rather than secondary measurements which may have an inherent lag before response to a flameout.

TABLE 19 . INCINERATION PROCESS FAILURE MODE ANALYSIS

PROCESS ELEMENT	FAILURE CAUSES	CONSEQUENCE
Tank Filling	- Overfill on level interlock failure	Waste spill
	- Leakage due to pump seal, valve packing material corrosion, etc.	Small waste spill
	- Inclusion of unauthorized waste by subversion of quality control procedures	Possible incineration difficulties
Waste Transfer thru Pump & Filter	- Leakage due to pump seal, material corrosion, etc.	Small waste spill
	- Deliberate bypassing of incinerator (ocean operations).	Waste spill
	- Filter plugging	None if filters switched on high pump discharge pressure measurement
Waste Injection to Incinerator	- Nozzle plugging (low flow detection)	Temporary shut-down
	- Atomization air loss on air blower failure	Failure to combust, toxic vapor discharge, liquid accumulation
Combustion	- Burner flame loss (flameout) due to fuel loss of pressure, loss of primary combustion, air, coking, or water slug in feed	Transient toxic vapor discharge prior to automatic shutdown on flame loss detection (or lower combustion temperature). (A water layer in the tank can be isolated by conductivity measurements and interlocked with the waste feed pump)
	- Improper fuel rate	Excess waste product in discharge
	- Improper air/fuel ratio	Inefficient combustion
	- Injection into a cool combustion zone on start-up	Inefficient combustion
Atmosphere		

DISCUSSION OF ENVIRONMENTAL IMPACTS: AT-SEA INCINERATION

Table 20 summarizes the major air and water quality effects that can be expected to result from at-sea incineration.

TABLE 20. SUMMARY OF MAJOR AIR AND WATER QUALITY EFFECTS ASSOCIATED WITH AT-SEA INCINERATION

Air Quality[a] ($\mu g/m^3$)				Water Quality (ppb)		
HCl	Inorganics[b]	Unburned[c] Wastes	Copper[d]	HCl	Unburned Wastes	Copper
4422	22.49	2.75	0.22	197	0.09	.04

[a]Maxima for stipulated meterological conditions: effective stack height = 125.5 meters, wind speed = 4.0 meters/second, and stability category = D.

[b]Based on summation of inorganic constituents in wastes; provides an estimate of particulate concentrations.

[c]Based on lowest average of observed destruction efficiencies (99.96%), as determined by different analysis methods.

[d]Copper and zinc are the metallic waste constituents with the highest emission rates.

The HCl concentrations are expected to be high because there is no scrubbing of the combustion gases. Due to its buffering capacity, one cubic meter of ocean water is capable of neutralizing 80 gm of HCl (80,000 ppb) [36]. Thus, a 197 ppb contribution of HCl from plume touchdown would never be detected by a pH change.

A Threshold Limit Value of 5 ppm has been established for HCl. This level represents the maximum allowable HCl concentration for humans in the work area. Excursions beyond this level for periods greater than 15 minutes result in either intolerable irritation, or chronic or irreversible tissue damage [37]. Maximum levels predicted as a result of at-sea incineration are below this TLV.

The predicted maximum ambient unburned waste concentration is close to four times larger than corresponding parameters predicted for the land-based facility. The difference is caused by differences in the emission rates and effective stack heights used for the two sets of simulations. The effects of these two differences are counteractive. As shown in Appendix B, predicted downwind concentrations are dependent on the magnitude of mass emission rates. The unburned waste emission rate for at-sea incineration is 7.3 times than that for the land-based facility. Thus, based on this fact alone, one would expect ambient concentrations predicted for at-sea incineration to also be 7.3 times larger. However, the higher effective stack height used for the simulations of at-sea incineration has the counteractive effect of reducing the magnitude of predicted ground-level downwind concentrations. For the simulations presented here, the overall effect of these reductions was to generate predicted unburned waste concentrations which were 38 times (as opposed to the 7.3 factor expected) larger than those for the land-based facility.

However, even through the concentrations within the plume from at-sea incineration are larger than those predicted for land-based facilities, these are nevertheless quite small. The maximum predicted level of 2.5 $\mu g/m^3$ corresponds to a concentration of 0.6 ppb if one assumes that the major waste constituent (dichloropropane) comprises all of the unburned waste. This maximum concentration is predicted to occur 4000 meters downwind from the ship. It is expected that diffusion processes will effectively decrease these concentrations at locations further downwind;if any remnants of the plume reach land (145 km away from the proposed North Atlantic burn zone) concentrations would be even lower.

The site and nature of environmental impacts associated with plume constituents will depend on plume behavior and the various physical properties of constituents within the plume. If conditions during the burn cause the plume to behave in a coning aloft mode, then gaseous plume constituents, (and particulates that are small enough to behave like gases), will be transported to points at varying distances downwind. During downwind travel, plume constituents will undergo continual dilution by diffusion type processes. If plume touchdown occurs at locations close to the ship, then the

corresponding air and water environments will be most affected by constituents which may be in the plume. More information on the size distribution of particulate matter will be required to determine whether particulates will be removed directly by gravity, or whether it will remain suspended and possibly serve as condensation nuclei.

During a 1974 burn of Shell waste aboard the M/T Vulcanus, water samples were obtained in the vicinity of plume touchdown [16]. Analyses of these samples showed no significant difference in pH and copper (the most abundant heavy metal constituent of the waste) as compared with samples from control areas. Organochlorine wastes were undetected at, in the water the 0.5 ppb level.

During this same burn, ambient air quality measurements were made by both ships and airplanes downwind from the M/T Vulcanus. HCl, the most abundant plume constituent, was measured and used as an indicator of plume location. Ground level concentrations of HCl ranged from 0.01 to 7 ppm, the maximum occuring of 926 meters downwind from the M/T Vulcanus. Aerial measurements indicate the plume reached a maximum attitude of 850 meters, and extended downwind to a distance of 2,400 meters at which point HCl concentrations were below the detection limit of 0.01 ppm. The highest concentration noted during aerial monitoring was 3 ppm.

Marine Biological Effects

Biological specimens (phytoplankton and zooplankton) were also taken during the 1974 burn [16]. Examination of chlorophyll-a (an indicator of phytoplankton activity) levels, and adenosine triphosphate (ATP) levels in the specimen showed no deleterious or subtle adverse impacts [16].

A series of biological tests were also associated with the March 1977 burn. Laboratory experiments with various concentrations of Shell waste culminated with the following results [38]:

- Seven of 14 fish (Fundulus Grandis) exposed to 74 ppm of Shell waste died within 41 hours. Death was apparently due to respiratory complications.
- At a concentration of 7.4 ppm, no effect on fish mortality was noted.

- o Enzyme systems (catalase and P-450) of fish exposed to 1.0 ppm showed a marked response.

The P-450 enzymes are located in the liver and are required for the metabolism of foreign chemicals introduced into an organism. The response noted (an increase in the P-450 activity) reflects the presence of an foreign material that has to be metabolically altered prior to excretion. This effect is seen as an indication of a potential problem.

In addition to the laboratory tests, the same fish species was exposed to the plume of the M/T Vulcanus during incineration. Exposure was accomplished by using a device called a Biotal Ocean Monitor (BOM), which allows specific organisms to be exposed under field conditions and then retrieved. The BOM tests showed an elevation in the activity of P-450 enzymes. However, when exposed fish were returned to the laboratory and left in clean water for a few days, the enzyme activity returned to the level found in control organisms.

The experimenters concluded that the overall effects are localized and temporary [38], and do not represent drawbacks to the use of at-sea incineration for organochlorine waste disposal.

Organic Materials Found During Combustion

Analysis of the feedstock for at-sea incineration is usually used to indicate the kinds of materials which would be delivered to the air and water environment. Recently, analyses of stack gases have indicated the presence of organic compounds which were not present in the original waste. Samples drawn from the stack of the M/T Vulcanus during the at-sea incineration of Herbicide Orange contained a variety of aromatic compounds which were not found in the original feedstock. Possible sources of these materials are synthesis in the flame or partial decomposition of waste feed. Conditions in the incinerator during Herbicide Orange combustion were: flame temperature average of 1500°C with a range of 1375°C (low) to 1610°C (high); dwell time or 1.09 sec (average) with a range of 0.91 to 1.31 sec; a waste feed rate of 14 - 15 tonnes/hour; and a waste destruction efficiency of 99.999% [35].

The presence of metals in liquid organochlorine wastes has been demonstrated. The metal content will appear in the stack gases (and thus the plume) as particulate matter. The quantity of metal salts or metal oxides in the plume is independent of combustion efficiency and is directly proportional to the metal content of the waste itself. Control of the metal content of waste which is accepted for at-sea incineration, becomes the responsibility of regulatory agencies to ensure that wastes with unacceptably high metal content are not approved for burning at sea. The control must be implemented, however, by restrictions based on air and water quality requirements. The metal content permitted in waste thus becomes a function of the plume model and of the at-sea incineration process, (e.g., dilution in the plume, feed rate of waste, total combustion air and speed of the incineration ship).

Currently there is no ship capable of burning solids in an acceptable manner. During past burns on the Matthias, entire drums of wastes were fed into the incinerator; there were indications of high particulate emissions. These emissions were due to the quantities and nature of inorganic constituents contained in the wastes and/or to the drum itself.

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APPENDIX A

DERIVATION OF PRODUCTION RATE FOR
ORGANOCHLORINE CHEMICALS, AND CORRESPONDING WASTES

Table 1 from the text is repeated below for the purpose of describing the derivation.

Table A-1. ESTIMATES OF NATIONAL ORGANIC CHEMICAL PRODUCTION AND CORRESPONDING WASTES.

	TOTAL PRODUCTION (in thousand tonnes)		
	1977	1983	1989
Organic Chemicals	93,435	143,578	201,254
Organic Wastes	2,302	4,249	6,354
Organochlorines	13,340	20,500	28,730
Organochlorine Wastes	440	606	907

The values for organic chemical production and organic wastes (the first and second rows in Table A-1) were obtained from a current investigation sponsored by the U.S. Maritime Administration [A-1]. Estimates for 1983 and 1989 are based on chemical growth rate and the expected impact of federal air, water and solid waste regulations on industrial waste generation. Air and water regulations will tend to increase the amount of residuals resulting from pollution control processes, while the regulatory requirements generated by the Resource Conservation and Recovery Act (RCRA) will tend to encourage recycling and recovery, thereby decreasing the quality of waste materials requiring disposal [A-1].

Total organochlorine production (third row) for the years noted was extrapolated from data generated by an organic chemical manufacturer [A-2]. In deriving the listed estimates, it was assumed that the production of organochlorine materials represented the same proportion of total organic chemicals in 1983 and 1989 as it did in 1977.

Except for 1977, estimates of organochlorine wastes (the fourth row) were obtained via the use of a factor which indicates the amount of wastes which are generated during the manufacture of organic chemicals. The factors used were determined empirically from the data in the first and second rows of Table A-1, and varied from 2.96% (for 1983) to 3.16% (for 1989). The organochlorine waste factor of 3.30% for 1977 was obtained from Reference [A-2].

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APPENDIX B

AIR QUALITY SIMULATION METHODOLOGY

A computer simulation of air quality impacts that would result from at-sea and land-based incineration was performed using the most representative set of physical parameters and meteorological conditions that could be determined from the available data. In this appendix the formulation of the model is presented and the inherent limitations of the analysis are discussed. The values of the input data are given and the results of a sensitivity analysis performed for two parameters are shown. The results of the air quality simulation are presented and the air impacts associated with at-sea and land-based incineration are briefly discussed.

TECHNICAL APPROACH

Downwind concentrations of gaseous pollutants can be simulated with a conventional Gaussian diffusion plume model which assumes a continuous point source of strength Q. The basic equation used in the calculation is

$$\chi(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left[-y^2/2\sigma_y^2\right] \left\{\exp\left[-(z-h)^2/2\sigma_z^2\right] + \exp\left[-(z+h)^2/2\sigma_z^2\right]\right\} \qquad \text{(B-1)}$$

where $\chi(x,y,z)$ is the concentration downwind from the source at x,y,z; Q is the continuous point source strength (i.e., emission rate); h is the effective stack height; u is the mean wind speed; and σ_y and σ_z are the horizontal and vertical standard deviations of the plume. In the above formulation the x-axis is aligned with the mean wind speed, the y-axis is in the crosswind direction, and the z-axis is in the vertical.

To obtain the downwind concentration at ground level, equation (B-1) simplifies to

$$\chi(x,o,o) = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left[-\frac{1}{2}\left(\frac{h}{\sigma_z}\right)^2\right] \qquad \text{(B-2)}$$

When gases and particulates are released from a point source they are carried downwind and are dispersed by atmospheric turbulence. Particulates will have an additional downward component of velocity at their terminal velocity, v_s. As the gases or particulates approach the ground, a fraction will be deposited on the surface or on vegetation by direct sedimentation, inertial impaction, adsorption, chemical reaction and other mechanisms. This removal causes the downwind flux of airborne gases or particulates to decrease. In the conventional Gaussian plume model described in Equation (B-1), no account is made for gravitational settling of particulates or for deposition mechanisms.

Overcamp [B-1] has proposed a modification of the Gaussian plume model for the deposition of fine and heavy particulates and gases. It combines a downward-sloping plume to account for settling and the assumption of a constant deposition velocity. The general equation for the concentration

$$\chi(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left[-y^2/2\sigma_y^2\right] \left\{\exp\left[-(z-h+\frac{v_s x}{u})^2/2\sigma_z^2\right]\right.$$

$$\left. + \alpha\{x'\} \exp\left[-(z+h-\frac{v_s x}{u})^2/2\sigma_z^2\right]\right\}$$

where $\alpha\{x'\}$ could be considered as that fraction of the plume that is reflected at the surface and $\alpha\{x'\}$ is defined as:

$$\alpha\{x'\} = 1 - \left[\frac{2v_d}{v_s + v_d + (uh - v_s x')(\sigma_z)^{-1}(d\sigma_z/dx)}\right]$$

where v_d is the deposition velocity and v_s is the terminal settling velocity. For a gas that is perfectly reflected at the ground, α is unity. It should be noted that x' is the point where the plume image streamline passes through the ground plane. An implicit equation for x' is:

$$z+h-\frac{v_s x}{u} = \left(h - \frac{v_s x'}{u}\right)\frac{\sigma_z(x)}{\sigma_z(x')}$$

The air quality simulation results presented in this report were not able to incorporate particulate settling or deposition mechanisms due to the unavailability of specific data. Particle size and the characteristics of the surface, among other parameters, would need to be known before settling and deposition could be included in the analysis. Therefore, ground-level downwind concentrations were calculated from Equation (B-2) using the most representative set of physical parameters and meteorological conditions that could be determined from the available data.

A word needs to be said about the diffusion and transport of pollutants over large bodies of water. It has been long known that the turbulence spectrum (and hence the diffusion) over water is different from that over land [B-2,B-3] at comparable stabilities. Raynor et al. [B-4] reported diffusion observations at sea which showed little spreading and marked departure from the standard Pasquill-Gifford curves. This apparently occurs for two reasons. First, the ocean surface is a dynamic one in contrast to the static land surface. Therefore, the roughness height, z_o, which among other parameters determines the turbulence intensity, becomes a function of the stage of wave development. Kitaigorodskii [B-5] derived expressions from determining an "equivalent sand roughness" element, z_s, of the sea surface. This value was found to be dependent on the Reynold's number at the surface. Second, density stratification over water is controlled not only by heat flux but also by water vapor flux because of the intense evaporation which takes place at the water surface. Monin [B-6] has taken this into account by redefining the stability parameter, L, in terms of the latent heat of vaporization, the Bowen ratio and the L which would occur over land.

Gifford [B-7] suggested in principle a method for obtaining the equivalent Pasquill-Gifford stability over water. He suggested that the z_s and L over water be first found, then the equivalent Pasquill-Gifford turbulence level be found from either Golder's [B-8] or Smith's [B-9] nomograms. Using values characteristic of the ocean, it was found that L could range anywhere between 20-40% of its "equivalent over-land" value, confirming the greater stability of the air mass over the ocean.

Portelli [B-10] recently reviewed the subject of diffusion over water. The turbulence intensity of the atmosphere over the ocean was found to depend

on (1) the temperature difference between the air and the ocean surface, and (2) the roughness of the ocean surface. It was difficult, however, to obtain quantifiable results (in particular for σ_y and σ_z) over the ocean which could be compared with the equivalent land values. Therefore, in this report, the at-sea values for these diffusion parameters were assumed to be the same as the corresponding land values.

LIMITATIONS OF THE ANALYSIS

There are a series of inherent problems and other factors which could have significant effects on the nature and applicability of results from this type of simulation analysis. In this section these problems and factors will be identified and measures taken (if any) to mitigate their effects will be be described.

The first problem involves inter-facility variations of those factors that affect effective stack height. Factors of importance include the following:

(1) The physical height of the stack's terminus above ground level (or sea level for ships)

(2) The ambient temperature lapse rate, effluent velocity, temperature of the effluent, and stack radius.

Numerical studies (e.g., see the sensitivity analysis performed in a later section of this appendix) have shown that ground level concentrations are strongly dependent on effective stack height. There is no simple way of designing this analysis to reflect these individual differences; therefore, the results in this report should be viewed as approximate concentrations expected to occur under the conditions imposed by a set of specified input parameters.

A second problem relates to differences in the meteorological conditions that may exist at individual facilities. Predicted ambient concentrations are strongly dependent on the selected meteorology. Atmospheric mixing over the ocean is generally conceded to be less than that over land, but the exact quantities are not yet known. As with the previous problem, there is no way of determining meteorological conditions that would be universally representative of at-sea and land-based conditions. However, information is presented

in the model input sections of this appendix which shows that the selection of meteorological parameters is validated to some extent by available data. The simulation was performed under a set of conditions which were considered to be the most representative of the land-based and at-sea facilities. It was assumed that these conditions would persist over long averaging times (on the order of 24 hours), even though such a persistance is highly unlikely. In addition, other special meteorological circumstances (fumigation, looping and trapping) may also be conducive to high pollution build-ups expecially around the land-based site.

Another level of difficulty stems from a void in our knowledge of aerosol scavenging and chemical reaction of pollutants in the atmosphere. Hydrogen chloride by virtue of its deliquescent nature, can be expected to be absorbed by moisture typically present in marine environments. HCl may also combine with other salt complexes and condensation nuclei present over the ocean. Similarly, unburned wastes and total organics may themselves enter into chemical reactions with marine aerosols or, at the very least, provide nucleation centers (condensation nuclei) for droplet formation. A determination of the consequences of the types of chemical reactions and the resulting scavenging of combustion products is beyond the scope of this study. However, in this analysis it is assumed that no scavenging takes place.

MODEL INPUT

The inputs to the diffusion model used for the air quality simulation in this report were the following: emission or discharge rate; effective stack height; wind speed; and atmospheric stability category.

The emission rates used as inputs to the model are shown in Table B-1. These emission rates were obtained from actual test data measured during the operation of at-sea and land-based incinerators [B-12, B-13, B-14, B-15]. Sections 3 and 4 of this report provide details on how emission rates were determined.

The physical stack height of the land-based incineration facility is 30 meters. The approximate distance of the top of the stack above the waterline for the at-sea facility is 15 meters. Effective stack height values were calculated to be 96.5 meters for the land-based facility and 125.5 meters for

TABLE B-1. EMISSION RATES USED FOR AIR QUALITY SIMULATION[a]

Constituent	Emission Rate (kg/hr)	
	At-Sea Incineration	Land-Based Incineration
HCl	14.16×10^3	0.895
Unburned Wastes[b]	8.8 (99.96% DE[c])	0.3
	2.2 (99.99% DE[c])	
Inorganics	72.0	
	53.0	
Particulates		1.03
F	1.0	
Cr	4.0	6.9×10^{-4}
Ni	2.0	6.9×10^{-4}
Ti		6.9×10^{-4}
Pb/Ti	0.4	
Cu/Zn	0.7	
As/Co	0.1	

[a]Emission rates are based on sampling and analysis data obtained at two operating facilities [B-12, B-13, B-14, B-15]. See Sections 3 and 4 of this report for a detailed description of now emissions were determined.

[b]The magnitude of this emission is determined by the use of destruction efficiency for the at-sea facility and detection limits for the land-based facility. See Sections 2 and 3 of this report.

[c]DE = Destruction Efficiency.

the at-sea facility. See Appendix E for the methodology that was used to determine these value.

A mean wind speed of 4.0 meters per second was used in all simulations. Table B-2 summarizes average wind speeds and directions for three on-shore sites closest to the North Atlantic area under consideration as a site for at-sea incineration. Averages at these three sites were 4.0 meters per second at Trenton, 4.6 meters per second at Newark and 4.8 meters per second at Atlantic City. The value of 4.0 meters per second was selected because the use of this value would result in higher ground level concentrations.

Table B-3 shows the annual percent frequency of Pasquill categories for all wind directions and speeds at seven cities across the United States. The D stability (neutral) is the most commonly occuring, while the A category (highly unstable) is the least. All simulations were performed for neutral (Class D) atmospheric stabilities.

SIMULATION RESULTS

Simulation of ambient air quality effects associated with at-sea and land-based incineration operations was performed using the model and inputs described in the previous section and the results are shown in Tables B-4 thru B-6.

TABLE B-2. AVERAGE WIND SPEEDS (METERS/SECOND) AND PREVAILING WIND DIRECTION FOR THREE COASTAL AREAS

	Atlantic City[a]		Newark[b]		Trenton[c]	
	Speed	Direction	Speed	Direction	Speed	Direction
	Meters/Second		Meters/Second		Meters/Second	
January	5.3	WNW	5.0	NE	4.4	NW
February	5.5	W	5.2	NW	4.6	NW
March	5.6	WNW	5.4	NW	4.8	NW
April	5.5	S	5.1	WNW	4.6	S
May	4.9	S	4.5	SW	4.0	S
June	4.3	S	4.2	SW	3.8	S
July	4.1	S	3.9	SW	3.5	S
August	3.9	S	3.9	SW	3.4	S
September	4.2	ENE	4.0	SW	3.5	S
October	4.4	W	4.2	SW	3.7	N
November	5.1	W	4.6	SW	4.1	SW
December	5.1	WNW	4.8	SW	4.2	NW
AVERAGES	4.8	S	4.6	SW	4.0	S

[a]Represents 16 years of data (1955-1970)
[b]Represents 31 years of data (1940-1970)
[c]Represents 32 years of data (1939-1970)

Land-Based Incineration

The highest ground-level concentration for land-based incineration can be expected from particulates. A maximum of 0.62 $\mu g/m^3$ occurs at 3 km downwind from the source. (See Table B-4).

TABLE B-3. ANNUAL PERCENT FREQUENCY OF PASQUILL STABILITY CATEGORIES FOR ALL WIND DIRECTIONS AND SPEEDS

	Pasquill Stability Category					
	A	B	C	D	E	F
Birmingham, Alabama	1	7	12	44	36*	
Tucson, Arizona	2	10	14	33	41*	
Los Angeles, Calif.	0	4	15	48	13	19
Miami, Florida	0	5	14	42	39*	
Chicago, Illinois	1	5	11	55	12	17
New York, New York	0	3	10	67	13	6
Philadelphia, Pa.	0	5	11	51	14	18

*Indicates E and F categories combined. (After Reference B-11).

Unburned waste concentrations from land-based incineration activities appear small. At 3 km downwind from the source concentration is 0.18 $\mu g/m^3$.

At-Sea Incineration

As shown in Tables B-5 and B-6 the highest predicted concentrations are due to HCl emissions. A ground level maximum of 4.42 $\mu g/m^3$ occurs at 4 km downwind from the ship.

The ambient levels for unburned wastes from at-sea incineration are much lower than for HCl. This is due to a lower emission rate for unburned waste as compared to that for HCl. In turn, the differences in emission rates are related to 1) the relatively high combustion efficiency of the incinerator, and 2) the fact that scrubbers are not used for at-sea incineration. Therefore, all HCl produced is emitted while unburned waste emissions are assumed to be, and in fact are, combustion efficiency limited. The maximum unburned waste concentration is calculated to be 2.75 $\mu g/m^3$ at a location 4 km downwind from the ship.

TABLE B-4. RESULTS OF AIR QUALITY SIMULATION FOR LAND-BASED INCINERATION: HCl, TRACE METALS, UNBURNED WASTE AND PARTICULATES[a]

Distance Downwind From Facility (Meters)	GROUND LEVEL CONCENTRATION			
	HCl (ng/m^3)	Trace Metals (Ti,Ni & Cr,ea) (ng/m^3)	Unburned Waste (ng/m^3)	Particulates (ng/m^3)
100	.00	.00	.00	.00
200	.00	.00	.00	.00
300	.00	.00	.00	.00
400	.00	.00	.00	.00
500	.07	.00	.02	.08
600	2.88	.00	.96	3.31
700	9.20	.01	3.09	10.59
800	31.03	.02	10.40	35.71
900	57.47	.04	19.26	66.14
1000	148.08	.11	49.63	170.41
2000	477.06	.37	159.91	549.02
3000	536.61	.41	179.87	617.55
4000	489.52	.38	164.09	563.36
5000	425.73	.33	142.70	489.95
6000	367.13	.28	123.06	422.51
7000	317.79	.25	106.52	365.72
8000	277.36	.21	92.97	319.19
9000	244.06	.19	81.81	280.87
10000	216.52	.17	72.58	249.18
20000	90.42	.07	30.31	104.05
30000	51.90	.04	17.40	59.73

[a]Simulation parameters were: effective stack height = 96.5 meters, and wind speed = 4.0 meters/second.

TABLE B-5. RESULTS OF AIR QUALITY SIMULATION FOR AT-SEA INCINERATION: HCl, UNBURNED WASTES AND INORGANICS.[a]

Distance Downwind From Ship (Meters)	HCL ($\mu g/m^3$)	GROUND LEVEL CONCENTRATION Unburned Wastes ($\mu g/m^3$)		Inorganics ($\mu g/m^3$)	
		99.96% DE[b]	99.99% DE[b]	High	Low
100	.00	.00	.00	.00	.00
200	.00	.00	.00	.00	.00
300	.00	.00	.00	.00	.00
400	.00	.00	.00	.00	.00
500	.00	.00	.00	.00	.00
600	.10	.06	.00	.00	.00
700	.84	0.00	.00	.00	.00
800	8.09	0.01	.00	.04	.03
900	25.43	0.02	.00	.13	.10
1000	144.67	0.09	.02	.74	.54
2000	2082.66	1.29	.32	10.59	7.80
3000	2849.86	2.39	.60	19.58	14.41
5000	4389.32	2.73	.68	22.32	16.43
6000	4116.79	2.56	.64	20.93	15.41
7000	3777.38	2.35	.59	19.21	14.14
8000	3438.65	2.14	.53	17.48	12.87
9000	3124.50	1.94	.49	15.89	11.69
10000	2843.01	1.77	.44	14.46	10.64
20000	1318.93	0.82	.20	6.71	4.94
30000	781.14	0.49	.12	3.97	2.92

[a]Simulation parameters were: effective stack height - 125.5 meters, wind speed - 4.0 meters/second.

[b]DE - Destruction efficiency.

TABLE B-6. RESULTS OF AIR QUALITY SIMULATION FOR AT-SEA INCINERATION: SELECTED TRACE ELEMENTS[a]

Downwind Distance From Ship (Meters)	Ground Level Concentration F (ng/m^3)	Cu/Zn (ng/m^3)	Pb/TI (ng/m^3)
100	.00	.00	.00
200	.00	.00	.00
300	.00	.00	.00
400	.00	.00	.00
500	.00	.00	.00
600	.01	.01	.00
700	.06	.04	.02
800	.57	.40	.23
900	1.80	.26	.72
1000	10.22	7.15	4.09
2000	147.08	102.96	58.83
3000	271.08	190.32	108.75
4000	312.34	218.64	124.94
5000	309.98	216.99	123.99
6000	290.73	203.51	116.29
7000	266.76	186.73	106.71
8000	242.84	169.99	97.14
9000	220.66	154.47	88.26
10000	200.78	140.54	80.31
20000	93.14	65.20	37.26
30000	55.17	38.62	22.07

TABLE B-6. (continued) RESULTS OF AIR QUALITY SIMULATION FOR AT-SEA INCINERATION: SELECTED TRACE ELEMENTS

Downwind Distance From Ship (Meters)	Ground Level Concentration As/Co (ng/m^3)	Cr (ng/m^3)	Ni (ng/m^3)
100	0.00	0.00	0.00
200	0.00	0.00	0.00
300	0.00	0.00	0.00
400	0.00	0.00	0.00
500	0.00	0.00	0.00
600	0.00	.03	.01
700	0.00	.24	.12
800	.06	2.28	1.14
900	.18	7.18	3.59
1000	1.02	40.87	20.43
2000	14.71	588.32	294.16
3000	27.19	1087.53	543.77
4000	31.24	1249.38	624.69
5000	31.00	1239.92	619.96
6000	29.07	1162.93	581.47
7000	26.68	1067.06	533.53
8000	24.28	971.37	485.68
9000	22.06	882.63	441.31
10000	20.08	803.11	401.56
20000	9.32	372.58	186.29
30000	5.52	200.66	110.33

SENSITIVITY ANALYSIS

The purpose of this sensitivity analysis is to describe the manner in which predicted ground level concentrations vary in response to changes in key input parameters. For the purpose of this analysis an emission rate of 6050 grams/hour was used.

Ground level concentration as a function of three effective stack heights is shown in Figure B-1. At an effective stack height, h, of 10.0 meters and a wind speed, u, of 0.5 meters/second, a peak concentration of 3040 $\mu g/m^3$ occurs at 0.5 km downwind. As h is doubled to 20 m, concentration is reduced to 810 $\mu g/m^3$ but now occurs further downwind at 0.9 km. Increasing the effective stack height to 30.0 m further reduces the ground level maximum concentration to 267 $\mu g/m^3$ which now occurs even further downwind at 2.0 km. An increase in the effective stack height by a factor of two causes approximately a four-fold decrease in ground level concentration and increasing the effective stack height by a factor of three causes approximately a 12-fold decrease in ground level concentration. This demonstrates the strong influence of effective stack height on ground level concentration.

The dependence of concentration on wind speed is shown in Figure B-2. Increasing wind speed by a factor of 2 reduces ground level concentration by exactly one-half. This may be inferred directly from Equation (B-1) in which concentration is inversely proportional to wind speed.

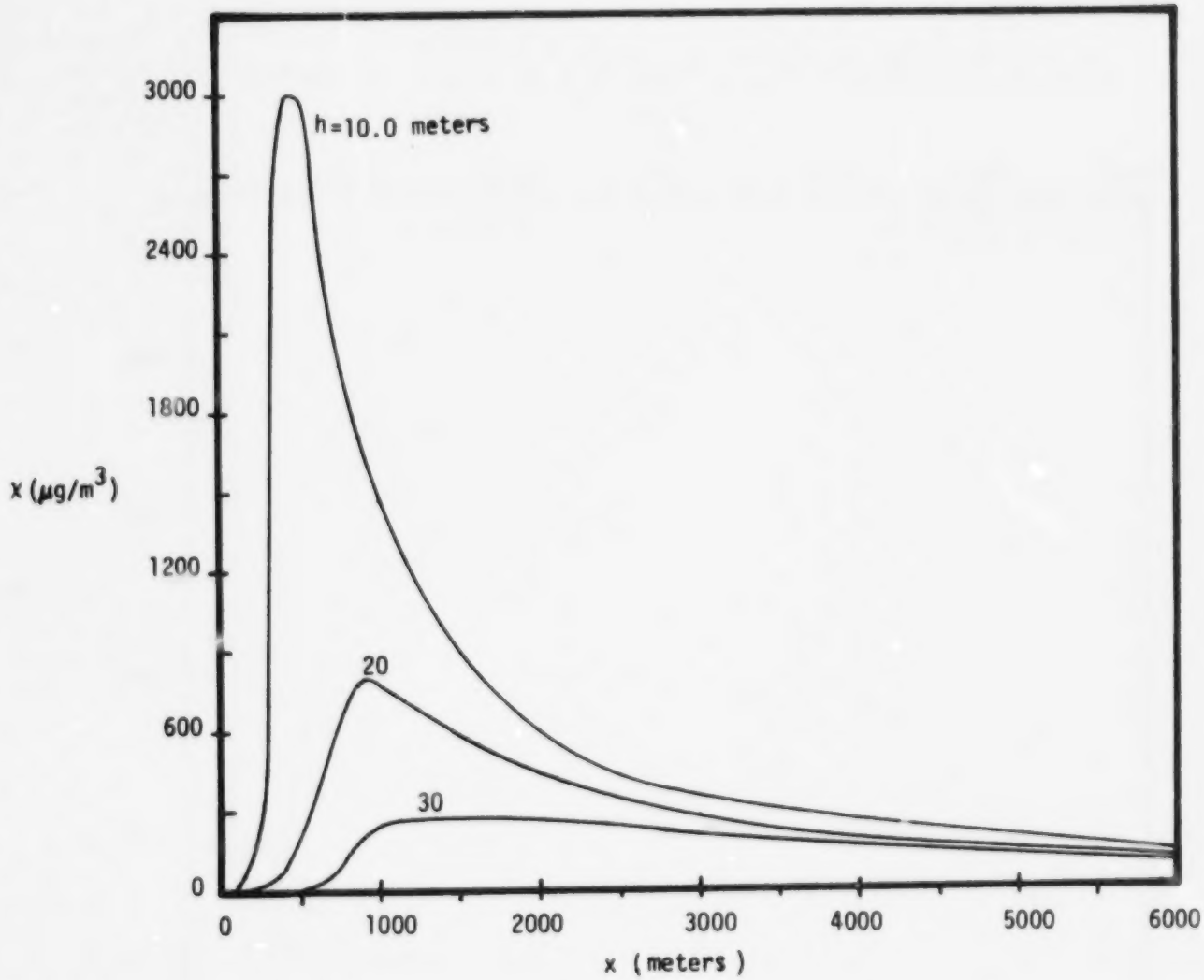

Figure B-1. Ground level concentration as a function of downwind distance at three effective stack heights, h. Emission rate is 6.05 kg/hr.

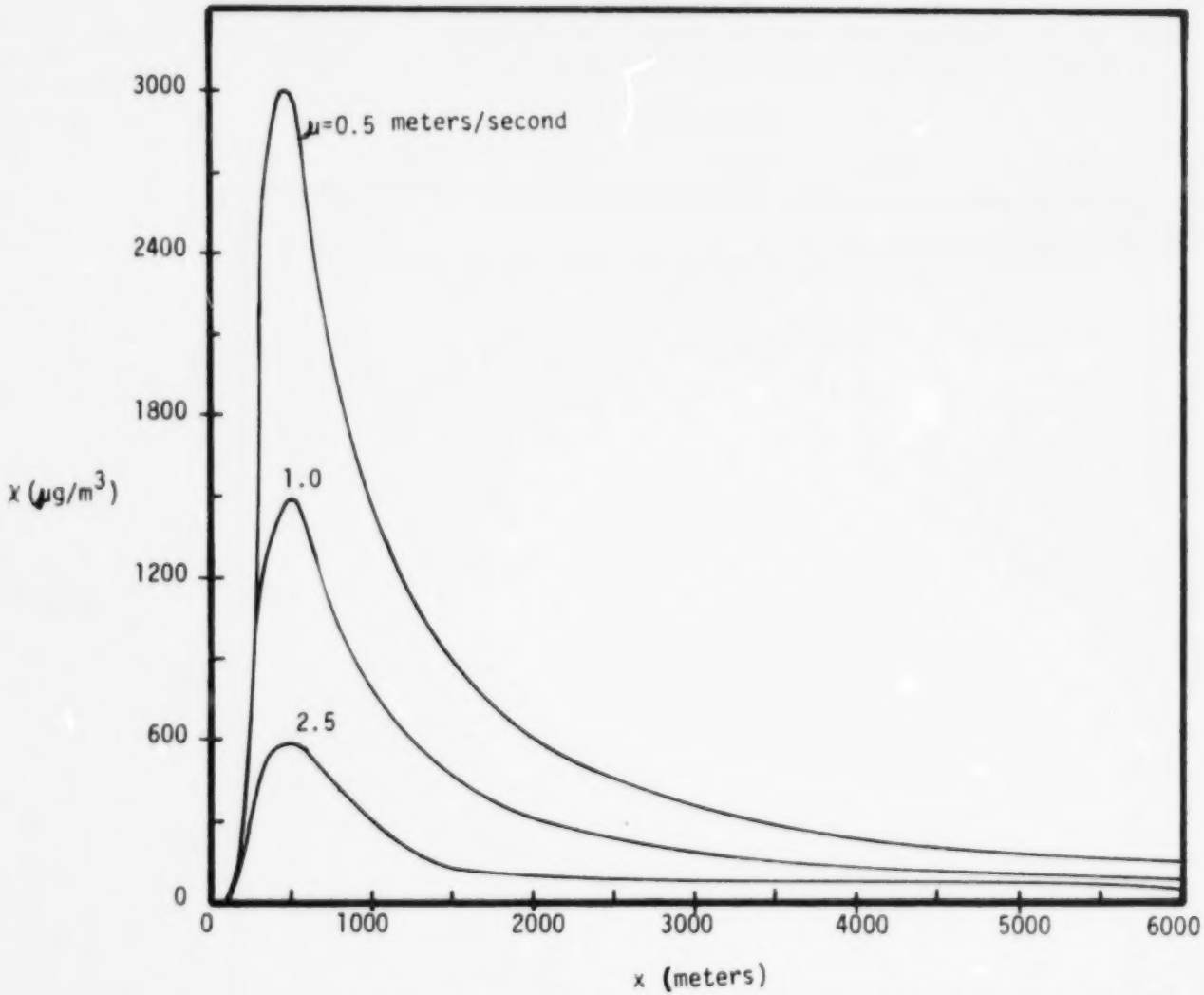

Figure B-2. Ground level concentration as a function of downwind distance at three wind speeds, u. Emission rate is 6.05 kg/hr.

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APPENDIX C

CALCULATIONS FOR CHARACTERIZATION OF
SINGLE PASS SCRUBBER WASTEWATER

Assumptions used for this analysis are:

1) All of the HCl formed during combustion is transferred into the scrubber wastewater. The maximum amount is assumed because this will be the worst case.

2) Seventy-five percent of the water feed to the scrubber is lost due to entrainment by the gas stream [C-1].

Analysis of scrubber wastewater quality at the Marquardt Company. Data obtained from reference [C-2].

Data:

Waste Incinerated	-	Hexachlorocyclopentadiene
Chlorine in Waste	-	76.5%
Caustic Feed Rate	-	23.8 liters/min
- type of caustic	-	12% NaOH - specific Gravity = 0.95
Water Feed Rate	-	60 liters/min
Waste Feed Rate	-	52.8 Kg/hr

Calculation of chloride content of scrubber wastewater:

equation 1.
$$\frac{(\%\ \text{Cl in waste})\ (\text{waste feed rate})}{(75\%)\ (\text{scrubber solution feed rate})} = \text{Chloride concentration in wastewater}$$

$$\frac{(.765)\ (52.8\ \text{kg/hr})\ \left(\frac{\text{hr}}{60\ \text{min}}\right)\ (1.0 \times 10^{6}\ \frac{\text{mg}}{\text{kg}})}{(.75)\ (73.8\ \text{l/min})} = 11{,}000\ \text{mg/l}$$

Calculation of calcium or sodium ion concentrations in wastewater

- Calculation of mass flow rate of solution

  23.8 liters/min x .95 kg/liter = 22.61 kg/min

- Calculation of NaOH flow rate at 12% of solution

  .12 x 22.61 kg/min = 2.71 kg/min NaOH

- Calculation of percent Na^+ ions at 57.5% of NaOH

  .575 x 2.71 kg/min = 1.56 kg/min

- Calculation of Na^+ ion concentration in wastewater

$$\frac{(1.56 \text{ kg/min})\ (1.0 \times 10^6 \text{ mg/kg})}{(.75)\ (73.8 \text{ liters/min})} = 25{,}700 \text{ mg/l}$$

Cl^-	ions -	11,000 mg/liter
Na^+	ions -	25,700 mg/liter
TDS		36,700 mg/liter

Analysis of scrubber wastewater quality at Rollins Environmental Services. Data obtained from reference [C-3].

Data:

Waste Incinerated	- Nitrochlorobenzene
Chlorine in Waste	- 10.0%
Caustic Feed Rate	- 8.5 liters/min
- type of solution	- 32% $Ca(OH)_2$ specific gravity 0.87
Water Feed Rate	- 3200 liters/min
Waste Feed Rate	- 1893 kg/hr

Calculation of chloride content in wastewater using equation 1.

$$\frac{(.10)\ (1893 \text{ kg/hr})\ (\frac{\text{hr}}{60 \text{ min}})\ (1.0 \times 10^6 \text{ mg/kg})}{(.75)\ 3200 \text{ liters/min}} = 1{,}314 \text{ mg/l}$$

Calculation of calcium concentration in wastewater

- mass flow rate of solution

  8.5 l/min x .87 kg/liter = 7.4 kg/min

- mass flow rate of $Ca(OH)_2$ at 32% of solution

  7.4 kg/min x .32 = 2.37 kg/min $Ca(OH)_2$

- mass flow rate of calcium ion at 54% of $Ca(OH)_2$

  .54 x 2.37 kg/min = 1.28 kg/min

- calculation of calcium concentration

$$\frac{1.28 \text{ kg/min} \times 1.0 \times 10^6 \text{ mg/kg}}{(.75)\ 3200 \text{ liter/min}} = 533 \text{ mg/liter}$$

Chloride ions -	1,300 mg/liter
Calcium ions -	530 mg/liter
TDS -	1830 mg/liter

REFERENCES

C-1 Final Environmental Statement; Disposition of Orange Herbicide by Incineration, Department of the Air Force, November 1974.

C-2 TRW Systems for U.S. Environmental Protection Agency, Office of Solid Wastes Management Programs, Facility 1 Report, Marquardt Company Destroying Chemical Wastes in Commercial Scale Incinerators, October 1976.

C-3 Arthur D. Little, Inc. Destroying Chemical Wastes in Commercial Scale Incinerators, 3M Company Chemolite System. Prepared for the U.S. Environmental Protection Agency, July 1977.

APPENDIX D

DEVELOPMENT OF MODEL TO DETERMINE THE EFFECTS OF AT-SEA INCINERATION ON OCEAN WATER QUALITY

Derivation of the model assumes stable conditions over the ocean and selects an arbitrary set of conditions of ship and speed. The model covers only those conditions under which the ship drives directly into the wind.

In this discussion a generalized representation is derived for the "footprint" of contours (in 2 dimensions) of isopleths of contaminants as a function of distance aft of the centerline of the incinerator on a vessel. The distance aft is designated x; the lateral dimension, y, is measured from a line (perpendicularly) represented by the ship's velocity (resultant of ship's speed and wind velocity) which is designated u. Distance above the ocean's surface is z.

A general expression is given by:

$$\chi = Q\left(\pi c^2 \chi^{(2-n)} u\right)^{-1} \cdot \exp\left[\frac{-y^2}{c^2 \chi (2-n)}\right]$$

$$\cdot \left\{\exp\left[\frac{-(z-h)^2}{c^2 \chi (2-n)}\right] + \exp\left[\frac{-(z+h)^2}{c^2 \chi (2-n)}\right]\right\}$$

Where:

χ = concentration of contaminant at x (meters) downwind and y (meters) off axis (of the moving ship), gram-moles/meters^3.

Q = source strength, gram-moles/sec.

c = diffusion coefficient (assumed isotropic) in the horizontal and vertical planes.

u = resultant velocity of the ship and wind velocity, meters/second.

n = nondimensional parameter associated with atmospheric stability

h = effective stack height (i.e., where the plume bends over) above the ocean surface, meters.

z = distance above surface of ocean in meters.

Because the ambient air over the surface of the ocean is slightly stable most of the time (approximately 90%), the value for $\underline{n}$ is taken as 0.25. The corresponding value for $c^2 = 0.014$ for an effective stack height of h = 24 meters.

As a representative example, $\underline{u}$ equals 10 meters/second. In the example, the total efflux from the stack of all constituents is Q = 4469 gm/moles/second with 7.06% being HCl, Q(HCl) = 315.5 gm/moles/second. For any other values of Q the results can be ratioed since X varies directly as Q. Thus at the ocean surface (z = 0).

$$\chi_{HCl}\ (\text{ppmv}) = \frac{3.214 \cdot 10^7}{x^{1.75}} \cdot \exp\left[-\frac{41{,}143}{x^{1.75}}\right] \cdot \exp\left[-\frac{71.43\ y^2}{x^{1.75}}\right]$$

This is for the case of Q_{HCl} = 315.5 gm-moles/sec and u = 10 meters/sec. The factor

$$F(x,y) = \exp\left[-\frac{71.43\ y^2}{x^{1.75}}\right]$$

defines reductions in concentrations off-axis. Table D-1 provides the multiplication factor for off-axis concentrations. Figure D-1 is a plot showing variations of off-axis concentrations of up to 120 meters. From the figure, one can make x-y plots of contours of equal concentration levels by replotting from the graph values for x and y, assuming a given value of concentration. For example, if one takes 10 ppmv and moves horizontally, one comes to values for y, beginning with y = 0, 10, 20, ... , etc., which correspond to values of x in meters (distance aft of the stack). In the case of y, which is the distance from the centerline defined by the ship's motion, one would plot points on both sides of the centerline.

The linear plot shows a true picture of the "footprint" of the plume (Figure D-2).

TABLE D-1. THE FACTOR (x,y) FOR A RANGE OF VALUES OF x AND y (x,y IN METERS)

y \ x	150	200	300	400	500	600	3000
0	1	1	1	1	1	1	1
10	.3292	.5109	.7187	.8190	.8738	.9065	.9941
20	.0117	.0681	.2668	.4500	.5825	.6752	.9768
30	.00004	.0024	.0512	.1658	.2965	.4132	.9485
40	0	.00002	.0005	.0410	.1151	.2078	.9103
50	0	0	.0002	.0068	.0341	.0858	.8634
60	0	0	0	.0007	.0077	.0234	.8094

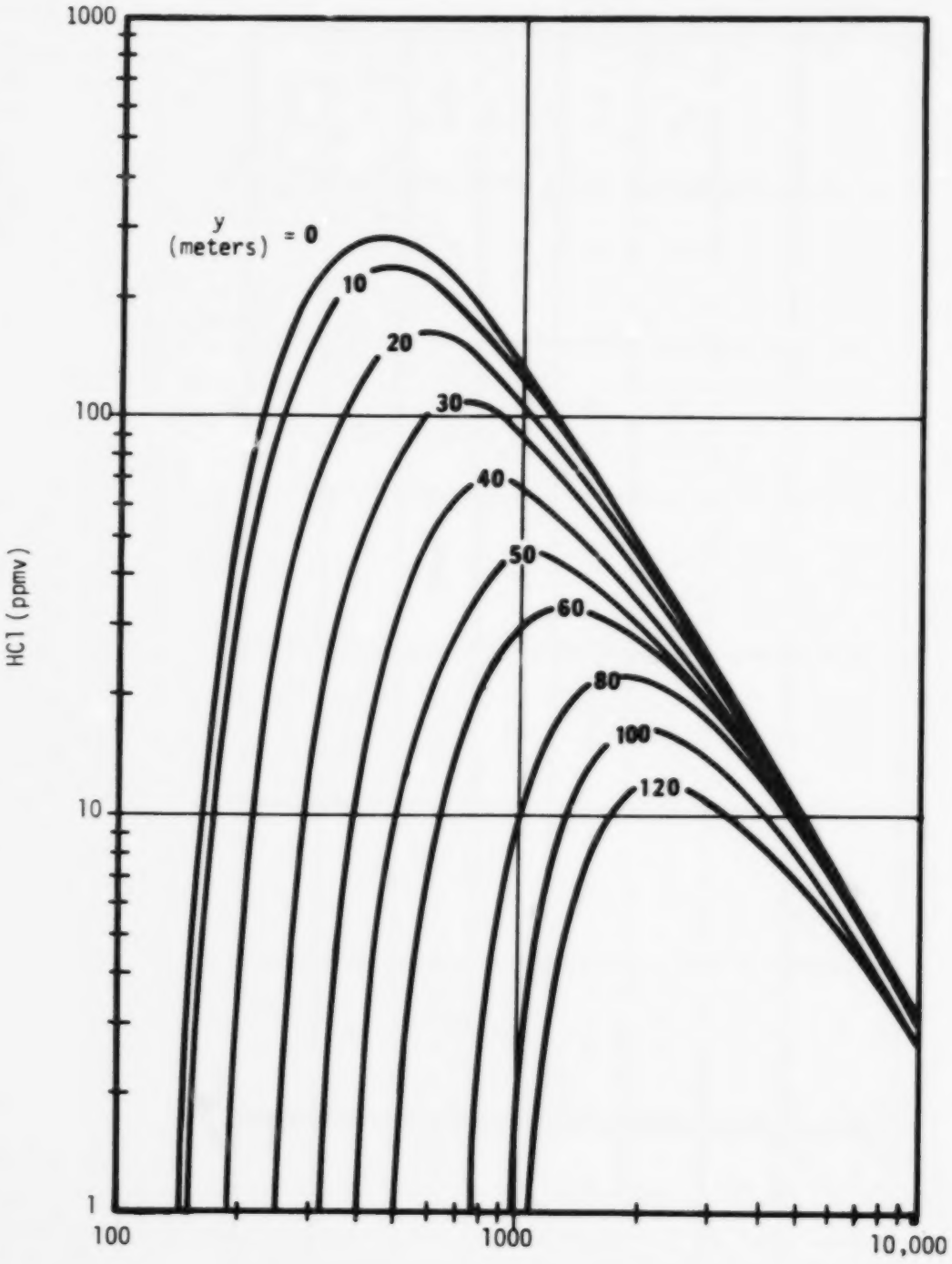

Figure D-1. Plot of HCl as a function of x and y.

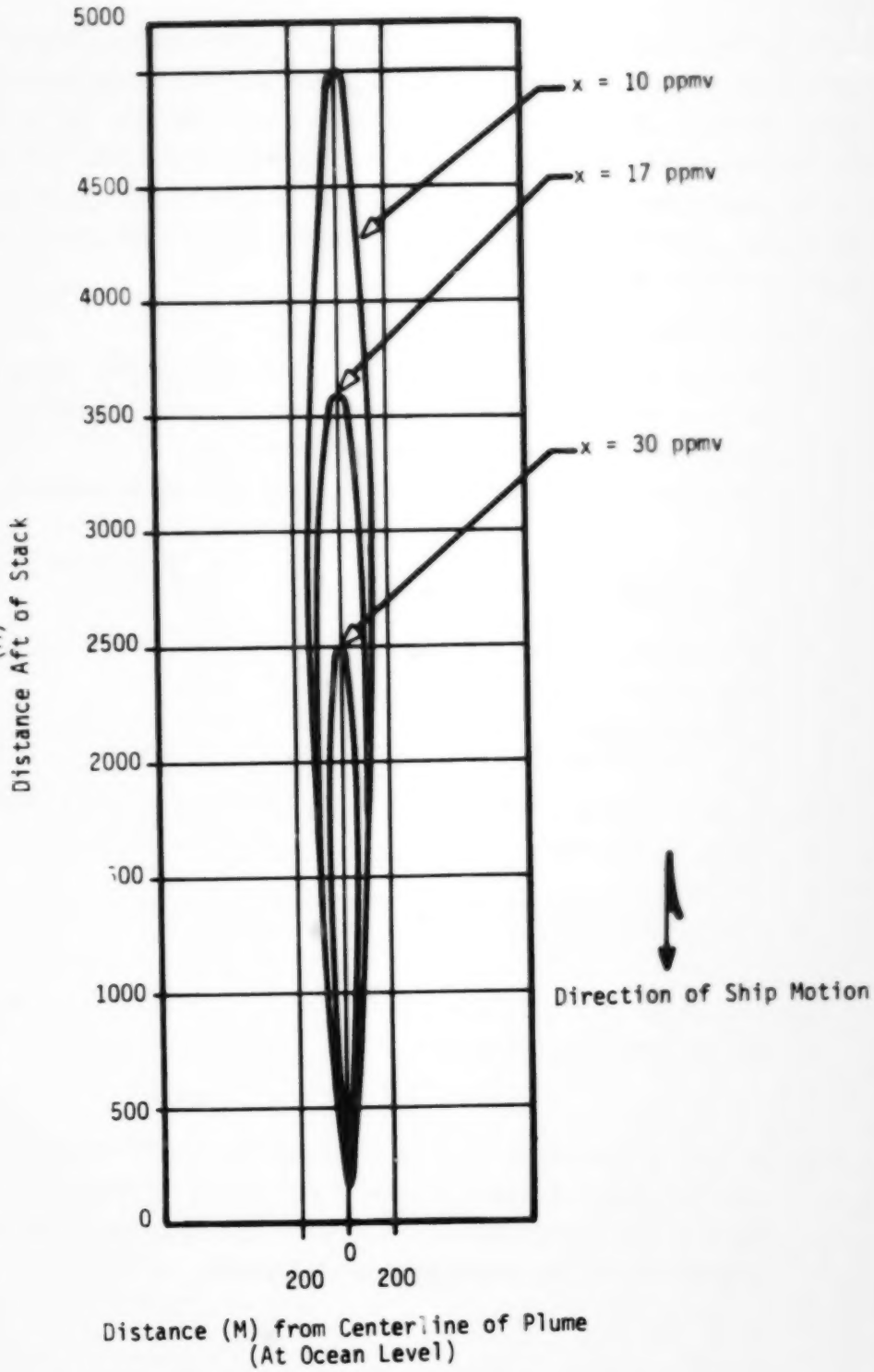

Figure D-2. Isopleths for HCl concentration (scale-linear)

If in the plume formula, u = 10 meters/sec (19.4 knots), assume the ship's speed to be 9.7 knots (5 m/sec) with an equivalent headwind of 9.7 knots (5 m/sec). With an effluent gas content of 7.06% HCl, the plume model described gives HCl isopleths as shown in Figures C-1 and C-2. It will be noted from Figure C-2 that the isopleth of 10 ppmv of HCl encompasses approximately an elliptical ocean surface pattern almost 5000 meters in length and at its widest point 270 meters wide.

From the available data, one may calculate:

1) An area of plume contact with the ocean surface (the footprint bounded by a 10 ppmv isopleth) is 1,060,288 meters^2. (Assume an ellipse, major and minor axes 5,000 and 270 meters.)
2) The plume is laid down across the ocean at 5 meters/second.

$$\left(\frac{9.7 \text{ kt} \times 6088 \text{ ft/hr}}{3600 \text{ sec/hr} \times 3.28 \text{ ft/meter}} \right) = 5 \text{ meters/second}$$

3) At 5 meters/second, one plume footprint (5000 meters x 270 meters) is laid down in 1000 seconds.

$$\left(\frac{5000 \text{ meters}}{5 \text{ meters/second}} \right)$$

4) An area of ocean equal to 3.6×10^6 meters^2 is thus covered by the plume in one hour.

$$\left(\frac{3600 \text{ second}}{1000 \text{ second}} \right) \times 1{,}060{,}288 \text{ meters}^2$$

5) The volume available for dilution is 7.2×10^7 meters^3, assuming the mixing zone to be 20 meters thick.

$$(3.6 \times 10^6 \text{ meters}^2 \times 20 \text{ meters})$$

6) A total of 8.8 kg/hr of unburned material is delivered to the ocean via the plume, assuming a waste feed rate of 22 tonnes/hr and a minimum destruction efficiency of 99.96%. The unburned material is assumed to be 100% organochlorine materials.

7) The concentration of material in the mixing zone is calculated as follows:

(Assume 8.8 kg of waste to be dissolved in 7.2×10^7 m^3). The diluted waste concentration is:

a) 1.22×10^{-6} mg/liter $\qquad \frac{8.8 \text{ kg} \times 10^3 \times 10^3}{7.2 \times 10^7 \times 10^3}$

b) 1.22×10^{-3} ppb $\qquad$ (ppm $\times 10^3$ = ppb)

The quantity of minor constituents in the waste, for example, copper (Cu), which would appear in the mixing zone can be estimated in a similar way. If a waste were to contain Cu at a 1.0 ppm level, the concentration in the mixing zone would be 3×10^{-4} ppb.

The emission rate of HCl has been calculated to be 14.16×10^6 gm/hour. Assuming that the total amount is dissolved in the ocean via the plume, the volume of water affected per hour is 7.2×10^7 m^3.

The concentration of HCl resulting from the above conditions is as follows:

$$\text{concentration HCl} = \frac{14.16 \times 10^6 \times 10^3 \text{ mg HCl/hr}}{7.2 \times 10^7 \times 10^3 \text{ liter/hr of ocean covered}}$$

concentration HCl = 0.197 ppm

APPENDIX E

DETERMINATION OF EFFECTIVE STACK HEIGHT

The effective stack height used in the air quality simulations is given by

$$h = h_s + \Delta h$$

where h_s is the physical height of the stack and Δh is the plume rise above the stack exit.

There are over 30 plume-rise formulas in the literature. All require empirical determination of one or more constants and some formulas are totally empirical. For the purpose of this analysis the Briggs plume-rise formula was chosen to calculate final rise in stable conditions with wind. This formula gave the minimum rise for the meteorological conditions chosen and it is valid for rise into stable air in which the stability parameter, s, is constant (E-1 and E-2). The equation is

$$\Delta h = 2.6 \left(\frac{F}{\mu s}\right)^{\frac{1}{3}}$$

where μ is the wind speed, s is a stability parameter and F is a quantity that is proportional to the rate of buoyancy emission from the stack. The stability parameter, s, is defined as

$$s = \frac{g}{T} \frac{\delta\theta}{\delta z}$$

where g is gravitational acceleration, T is the absolute temperature of the ambient air, and $\frac{\delta\theta}{\delta z} = \left(\frac{\delta T}{\delta z}\right) + 9.8°C/km$, the potential temperature gradient. A value of -1.5°C per 100 m was used for $\frac{\delta T}{\delta z}$. The buoyance flux, F, can be expressed as

$$F = \frac{\Delta T}{T_s} gwr^2$$

where ΔT is the stack effluent temperature minus the ambient air temperature, T_s is the absolute temperature of the stack air, w is the stack-gas effluent velocity, and r is the inside radius of the stack.

Table E-1 lists the input data used in the plume rise calculations. Using this data, effective stack heights of 96.5 m and 125.5 m were found for land-based and at-sea incineration, respectively.

TABLE E-1. INPUT DATA USED IN PLUME RISE CALCULATIONS*

	Land-Based Incineration	At-Sea Incineration
Temperature of stack air (C)	60	1200
Temperature of ambient air (C)	20	20
Stack radius (m)	1.0	1.7
Stack-gas effluent velocity (m/sec)	8.7	2.3
Stack height (m)	30	15
Wind speed (m/sec)	4.0	4.0

*Based on information contained in References E-3 and E-4.

REFERENCES

E-1. Briggs, Gary A, et al., Meteorology and Atomic Energy, David H. Slade, ed., U. S. Atomic Energy Commission, TID-24190, July 1968

E-2. Briggs, Gary A., Plume Rise, U. S. Atomic Energy Commission, TID-25075, Nov. 1969.

E-3. TRW. Destroying Chemical Wastes in Commercial Scale Incinerators; Facility Report No. 6. Prepared for the U. S. Environmental Protection Agency, June 1977.

E-4. U. S. Environmental Protection Agency. At Sea Incineration of Organochlorine Wastes On-Board the M/T Vulcanus. EPA-600/2-77-196, Sept. 1977.